Toughness Evaluation of Electrogas and Electroslag Weldments

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TOUGHNESS EVALUATION OF ELECTROGAS AND ELECTROSLAG WELDMENTS

MARCH 1975

FOREWORD

This investigation presents the results of one of the research and development programs that was initiated by the members of the Ship Production Committee of the Society of Naval Architects and Marine Engineers and financed largely by government funds through a cost sharing contract between the U. S. Maritime Administration, Bethlehem Steel Corporation and the American Bureau of Shipping. Mr. W. C. Brayton, Bethlehem Steel Corporation was the Program Manager. The program objective emphasizes productivity; the work was carried out to assess mechanized electrogas and electroslag welding processes for hull construction.

The program was carried out by the American Bureau of Shipping under the general direction of Mr. K. D. Morland and Mr. E. D. Swenson. Mr. B. L. Alia, was the Project Manager and Mr. I. L. Stern and Mr. C. Null served as Project Engineers. The service provided by members of the American Bureau of Shipping Metallurgy Laboratory under the technical laboratory supervision of Mr. C. R. Herbst is gratefully acknowledged.

In addition, the services of Bethlehem Steel Corporation, Sparrows Point Shipyard in preparing the test weldments and the U. S. Naval Ordnance Station, Manufacturing Technology Department, Louisville, Kentucky in conducting the explosion bulge tests are acknowledged.

Finally, the assistance provided by Airco Welding Products Division of Air Reduction Company, Inc., Linde Division of Union Carbide Corporation and The Lincoln Electric Company in the preparation of exploratory weldments is appreciated.

EXECUTIVE SUMMARY

BACKGROUND

Recent modernization in shipbuilding methods and facilities in both foreign and U.S. shipyards has been directed in large part to improvements in welding technology. Higher deposition rates offered by automatic and semi-automatic processes offer substantial cost savings in many areas of shipyard welding.

Processes such as electroslag and electrogas welding of vertical side shell and bulkhead butts produce welds which offer better appearance and uniformity at substantially lower cost than manual stick electrode welding. Unfortunately high heat input at comparatively low travel speeds adversely affects the toughness properties in both the weld and the heat affected zone. Charpy Vee notch tests are the basis of evaluation used by ABS and other classification organizations to evaluate toughess. In view of the relatively large and increasing extent of these welds it is felt that a more definite criteria of toughness should be established.

More enlightenment in this area might justify relaxation of some of the present restrictions particularly with respect to higher strength steels used in high stress areas such as the bilge and shear strake.

OBJECTIVES

The primary objective of the program is to develop a basis for relaxing some of the current limitations on the applicability of electrogas and electro - slag welding processes to commercial shipbuilding.

A second objective is to compare the properties of electrogas and electroslag welds with those of other welding processes such as manual metal arc and submerged arc currently used in comparable applications.

A third objective is to define those potential electrogas and electro-slag applications for which modification of base plate and/or filler electrode might be required and to develop a basis for determining the extent of modification(s) required.

ACHIEVEMENT

In an exploratory program of the depth and scope of this one it *is* not possible to draw many broad conclusions; however, results have indicated several areas of information which should prove helpful in developing the technology to extend the use of high heat input processes such as electrogas and electroslag welding to appropriate areas in shipbuilding.

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2. Pellini, W. S. and Puzak, P. P. - "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design on Steel Structures," NRL Report No. 5920, U. S. Naval Research Laboratory, 1963. .
3. Hartbower, C. E. and Pellini, W. S. - "Investigation of Factors which Determine the Performance of Weldings," Welding Research Supplement, Oct. 1951 p.504-s.
4. Pellini, W. S. - "Principles of Fracture-Safe Design," Part 11, Welding Journal, Vol. 50, No. 4, Research Suppl. 147-S, April 1971.
5. Rolfe, S. T., Rhea, D. M. and Kugmanovic, B. O. - "Fracture Control Guidelines for Welded Steel Ship Hulls," Ship Structure Committee, Ser. No. SSC-244, 1974.
6. Annual Book of ASTM Standards, Part 31, Designation; E208-69: American Society for Testing and Material, pp. 597-616.
7. Puzak, P. P. and Pellini, W. S. - "Standard Evaluation Procedures for Explosion Bulge Testing (Weldments)," NRL Memorandum Report 1255, U. S. Naval Research Laboratory, Dec. 1961.
8. "Standard Procedures for Preproduction Testing Materials by the Explosion Bulge Test," NAVSHIPS 0900-003-5000 Rev. 1, Bureau of Ships, Navy Department, Washington, D. C. November 1965.

1.0 INTRODUCTION

The nation's shipbuilding industry is aware of the beneficial effect that completely automated high deposition rate welding processes such as vertical electrogas (EG) or electroslag (ES) methods could have on productivity, overall quality and consistency of construction. These advantages are particularly applicable to current building proposals that call for a number of ships or structures of the same design and for large ships where quantities of straight and parallel plates are used, and for structures with uniform shapes such as cylindrical and spherical tanks. One potential advantage of these automated high deposition processes is indicated in Table 1 which compares speed and deposition rates of EG and ES with other welding processes, in a typical vertical shell joint.

1.1 BACKGROUND

The EG and ES processes have been utilized in ships classed by American Bureau of Shipping and other regulatory bodies for several years. One of the principal applications of the EG and ES processes has been for the vertical welding of the straight portion of the side shell, from the bilge area up the side shell to the sheer strake; usually a length of approximately 40-70 feet depending on the size of the ship. In most cases this involves welding ABS Grade A and B ordinary strength hull steel of about one inch in thickness. Conventional methods of making these welds are the manual metal arc (MM) or gas metal arc (GMA) welding processes. Figure 1 illustrates typical side shell butts showing currently used welding processes. Additional shipbuilding applications of the EG and ES processes have been the vertical welding of butts In deck slabs and bottom longitudinals, face plates of shell girders, heavy sections of fabricated rudder horns and stern frames.

The increased cost of capital equipment and the greater set-up time associated with the EG and ES processes are generally compensated by the efficiencies of these automated processes. Aside from consideration of equipment cost and set-up time, the principal limitation of the EG and ES processes is related to the degrading effects of the relatively high heat input on the toughness of the heat affected zone (HAZ) of notch tough steels.

Figures 2 and 3 contain a photomacrograph and photomicrographs of a typical EG weld in a normalized higher strength hull steel. As indicated in Figure 3, the high heat input produces in the HAZ, a localized area, approximately 2 to 3 mm wide, of reactively large grain size. In notch tough fine grain normalized steels, this grain coarsened region is associated with a reduction in notch toughness properties. In view of possible degradation, Charpy V-notch (CVN) tests of the HAZ are currently required by ABS to qualify EG and ES welding procedures when they are proposed for special applications such as the sheer strake. When such tests indicate low HAZ CVN toughness, applications of the EG and ES procedures are limited to areas where toughness is not a primary consideration. If HAZ toughness degradation in EG and ES welds could

The above limitation on the EG and ES processes is based primarily on HAZ CVN toughness data. This test method has been used for many years in evaluating base material and welds, and various researchers have made correlations between the CVN energy and the tendencies for crack initiation and arrest. However, CVN values represent only a small area, and one of the considerations upon which this investigation was based is that small scale toughness tests may not be representative of the actual structural behavior of the entire welded joint; particularly since the CVN values vary considerably across the weld joint and the unacceptable low values usually involve a region in the HAZ only 2 to 3 mm wide.

Recent work(1) on correlation of CVN tests with large scale Robertson tests indicated that criteria based on the lowest CVN values in the HAZ might be excessively restrictive and may not necessarily correlate with overall joint performance. This indication offers the possibility of modifying the ABS requirement for HAZ CVN testing (current limiting criteria) with a more meaningful and possibly less restrictive criteria and thus be more representative of both overall joint performance service conditions.

1.2 Previous Work

The Bureau has accumulated substantial HAZ CVN data from shipyard EG and ES welding procedure tests in Grades A, D, C, CS, AH32, AH36, DH32 and EH36 hull steels. Some typical CVN data obtained from these procedures are shown in Table 2. In addition, the Bureau conducted preliminary tests with small scale weldments to evaluate HM toughness of EG and ES weldments using base material and typical welding parameters and filler materials as shown in Table 3. Table 4 indicates the mechanical properties and chemical composition of these materials. Table 5 indicates the CVN base material, weld metal and HAZ results. Included in Table 5 are the test results for ASTMA203 Grade A, a 28. Nickel alloy steel. HAZ CVN test results of the EG and ES weldments in Table 5 indicate a significant decrease from the base material impact values in all normalized steels except the ASTMA203 Grade A steel and no significant decrease in HAZ toughness for the as-rolled Grade B steel.

1.3 Project Objective

The primary objective of this project was to determine if some of the current limitations on the applicability of EG and ES processes to commercial shipbuilding could be relaxed.

A secondary objective was to determine the extent to which CVN and other small scale toughness tests are indicative of the composite joint toughness.

1.4 Approach

The overall approach was to evalute the performance of EG and ES weldments as compared with the more commonly accepted MMA and submerged arc welding (sAw) processes. As discussed previously, MMA has been widely used for vertical position butt welds in special notch tough material such as ABS Grades CS, E, and EH fitted in way of the sheer and bilge strakes of larger ships. SAW with single or multiple arcs has been used to make flat position erection butts in the decks of large ships. In ships such as general cargo,. container or ore carriers the deck stringer plates may be of special notch tough material such as ABS Grades CS, E or EH and thus have been welded by SAW when making erection butt welds in the deck. When MMA for butt welding of sheer and bilge strakes and SAW for butt welding of the deck stringer plates has been used, there has been no evidence of unsatisfactory performance or brittle fractures in way of these welds. In these applications the MMA process represents a low heat input process, approximately 50,000 joules/in. and the SAW a higher heat input process, approximately 75,000 to 100,000 joules/in. In this investigation a tandem, triple arc SAW process with a heat input of approximately 75,000 joules/in. for each arc was utilized. This high deposition SAW technique is currently being used by many shipyards. Due to the close proximity of the three arcs, it is probable that the total heat input is somewhat additive, however,si.nce there is lack of complete agreement on how to calculate the total heat input, the highest calculated single arc heat input is indicated in Table 6.

Small scale toughness tests including CVN, dynamic tear (DT) and the drop weight test (DMT) were conducted on the base material, weld and HAZ. Explosion bulge tests were conducted to evaluate the combined joint toughness and are considered appropriate for this investigation because of the extensive background information available on this test, and its correlation with service. [2,3] The explosion bulge test is a unique test in which a sudden uniform load is applied stiultaneously to the base material, weld and HAZ and evaluates the performance of the weldment. The test employs a rather large test specimen as illustrated in Figures 4 and 5. It is an expensive test and only a few establishments in the U.S. have the necessary explosion test facilities. As a result, selection of this test for general shipyard welding procedure tests is considered impractical. An attempt was made to relate the results of the large scale explosion bulge tests to the small scale tests that are more practical for general shipyard procedure evaluation.

The selection of CVN, DT and DWT small scale toughness tests, using the specimen types as illustrated in Figure 6 were based on the following:

Charpy V-notch (CVN) - This test was selected because it is the most widely used and most economical toughness test and forms the basis for ABS base material and weld metal requirements. The practice of evaluating and testing the HAZ by CVN, though questioned by some researchers, is none the less the toughness test usually specified by most designers and regulatory bodies. As indicated previously, ABS requires such testing when EG and ES welding procedures are used for special applications where retention of notch toughness is primary consideration. CVN test temperatures selected for this investigation item relate to the temperature appropriate to the base material. (See 6.4).

Dynamic Tear (DT) - This test was selected because researchers[4] have claimed that the DT results are more representative of sevice than the CVN test. In this investigation a 5/8 in. thick specimen was used, since this size specimen is a proposed standard, and testing can be carried out in a shipyard using modified DWC machine equipment. Figure 7 illustrates the modification of the DWT apparatus for conducting DT testing. Energy is determined from measured deformation of the replaceable aluminum blocks shown therein. A 70F test temperature was selected, since it had been claimed to be appropriate to the DT evaluation of hull steels.[5] A second series of tests were conducted at lower temperatures and reflect the same temperature selected for the CVN tests.

NDT Drop Weight Test (DWT) - This test was selected because it is a test used to define the nil ductility temperature (NDT). The NDT temperature is determined by conducting drop weight tests at suitable temperature intervals to establish the limits within 10F for break and no break performance as shown in Figure 8. The NDT is 10F lower than the lowest duplicate no break temperature. DWT is often utilized as an alternate to the CVN test and the necessary equipment is available in many shipyards. The method of conducting this test is described by ASTM A208. (6)

2.0 MATERIAL SELECITION

Four different material grades were selected for the test program; ABS Grades B, CS, EH36, and ASTM A203 Grade A 2¼% Nickel alloy steel. Single plates approximately 8 ft. wide by 30 ft. long of each grade were ordered and obtained to enable weld tests for each welding process to be made from the same plate, thereby eliminating the factor of different plates of the same grade as an experimental variable. Grade B in 1 in. thickness was selected because of frequent use of this grade and thickness as side shell plating; Grade B is a typical as-rolled semi-killed steel. Grades CS and EH36 in l¼ in. thickness were selected because both are fully killed fine grain normalized steels frequently used in the sheer . and bilge strakes; CS for ordinary strength designs and EH36 for higher strength designs. ASTMM A203 Grade A steel 1¼ in. thick was selected because the preliminary test results of EG welds in this material had revealed little or no degradation in HAZ toughness properties as measured by CVN tests. The possibility of substituting a nickel alloy steel such as ASTM A203 Grade A for either Grades CS or EH36 for special applications where EG or ES welding was anticipated might be considered provided HAZ toughness proved satisfactory.

3.0 WELDMENT PREPARATION

Each plate was cut into 8 ft. by 20 in. sections. Two 8 ft. long weldments were made from each grade of material with the MMA, SAW, EG and ES welding process. All welds were perpendicular to the direction of rolling. Welding parameters used are shown in Table 6. Typical composition of filler metals are shown in Table 7. On the basis of preliminary tests or available data, all the filler materials selected were expected to exhibit CVN toughness comparable with the base material. All welds except the EG welds were made at a shipyard under typical production conditions. The EG welds were made at an equipment manufacturer’s plant under the surveillance of shipyard personnel. and are believed to be representative of typical shipyard production methods.

4.0 TESTING PROCEDURES

4.1 Evaluation of Base Material

The following tests were conducted on each grade of base material:

- Chemical analyses
- Longitudinal tensile tests
- Charpy V-notch (CVN) longitudinal and transverse tests (to develop CVN curves)
- Dynamic tear (DT) tests (to develop DT curves)
- Drop weight tests (DWT) (to determine NDT temperature)
- Photomicrographs
- McQuaid-Ehn tests (to determine austenitic grain size)

4.2 Evaluation of Weldments

4.2.1 Nondestructive Testing

Weldments were evaluated by 100% radiographic and ultrasonic testing to the applicable Class A requirements specified in the ABS “Requirements for Radiographic Inspection of Hull Welds” and the ABS “Requirements for Ultrasonic Inspection of Hull Welds.”

4.2.2 Small Scale Testing of Weldments

The following small scale tests representative of each welding process were conducted for each grade of base material:

- Two transverse tensile tests
- Two guided side bend tests
- Two all weld metal tensile tests
- CVN tests with notches located at the centerline of the weld, the fusion line and the HAZ at 1 mm, 3 mm, 5 mm, 7 mm, and 9 mm from the fusion line, as shown in Figure 9.
- DT tests at two temperatures with the notches located at the centerline of the weld and the HAZ as shown in Figure 10.
- DWT tests to determine the NDT temperatures with notches located in the crack starter bead at the centerline of the weld and the HAZ as shown in Figure 11.
- A hardness survey of the weld and HAZ.
- Photomacrographs and photomicrographs of the weld and HAZ.

4.2.3 Notch Locations

Figures 9 through 11 illustrate the locations of the notches with respect to the various test methods as a function of the welding process. As indicated therein, the proportion of weld, HAZ and unaffected base material in each test varies considerably. This variation is dependent primarily on the welding process, joint design and test method.

4.3 Crack Starter and Explosion Bulge Testing

4.3.1 Testing Set-up

Explosion bulge testing was conducted using standard procedures.[7] [8] Typical specimen, die and set-up are shown in Figures 4 and 5. Test temperatures were established to provide for a reasonable degree of deformation in MMA and SAW specimens so that comparative data with the EG and ES specimens could be obtained. Test temperatures below ambient were obtained by placing the specimen in a specially designed freezer box for sufficient time to insure eqtilization at a temperature slightly below the test temperature. The test temperatures above ambient were obtained by placing the specimen in a bath of heated water for sufficient time to insure equaltiation at a temperature slightly above the test temperature. The specimen temperature change between removal from the freezer or hot water bath and setting off the explosion charge had been previously established and was taken into account during cooling and heating of specimens. In accordance with standard procedure,[8] the weight of the pentolite explosive charge, and the standoff distance were established for each thickness by determining the parameters which would produce an approximate 3% thickness reduction on the first shot. Data relative to charge, standoff distance and thickness reduction can be found in Table 8; the specimens are illustrated in Figure 12. Crack starter test data on Grades B and CS base material are indicated in Table 9, and the performance of each test specimen is illustrated in Figures 13 and 14. As indicated therein no crack propagation to the hold down region occurred after one shot at each respective test temperature. Previous tests conducted at lower temperatures had revealed crack propagation into the hold down region and, in some cases, plate separation. Based on the crack starter tests and results reported[2] the below listed test temperatures which are approximately 100F above the material NDT (as determined by DWT), were selected for the explosion bulge test of the various weldments:

Grade Steel	NDT Drop Weight	Explosion Bulge Test Temp. (F)
B	20	120
Cs	-70	20
EH36	-90	0
ASTM A.203 Grade A	-100	0

Two explosion bulge specimens representative of each base material grade and welding process were tested at the selected conditions. Each specimen was subjected to three shots or separation, whichever occurred first. In some cases where the duplicate results were inconsistent, additional specimens were tested. After each shot the specimens were examined, location of cracks noted and thickness reduction and bulge height measured. After completion of the test the fracture surfaces of the specimens were examined visually, and representative sections of the fractures were examined.

5.0 TEST RESULTS

5.1 Base Material

Results of chemical analysis and mechanical tests of each grade of base material are shown in Tables 10 and 11. The results of the CVN, DT and DWT tests are graphically shown in Figures 15 through 18. The photo-micrographs and McQuaid-Ehn test results for each grade of material are shown in Figures 19 through 22.

5.2 Evaluation of Weldments

5.2.1 Small Scale Tests

The results of the tensile, bend and small scale toughness tests of each welding process for each grade of base material are indicated in Tables 12 through 15. Figures 23 through 26 graphically illustrate the weld metal and HAZ CVN results for each material. Figures 27 through 30 graphically illustrate the HAZ DT results for each material. Macrosections representative of each weldment are illustrated in Figures 31 through 34. Hardness surveys across the welds are indicated in Tables 16 through 19. Photomicrographs of the weld metal and HAZ representative of each material and welding process are illustrated in Figures 35 through 50. Relationships between DT energy and fracture appearance are shown in Figure 51.

5.2.2 Explosion Bulge -

Figure 52 shows representative bulge specimens for each material and welding process which sustained 3 shots without cracking. The results of all explosion bulge tests are indicated in Tables 20 through 23; appropriate photographs are illustrated in Figures 53 through 63. Figures 64 through 66 illustrate macrosections and micrographs of areas of separation in EG and ES welds. Comparisons between explosion bulge and small scale toughness test results are shown in Tables 24 through 27.

6.0 ANALYSIS OF RESULTS

6.1 Base Material Evaluation

All results of the base material tests met the requirements of the representative material grade. The base materials used in this investigation may be considered typical of the representative material grade.

6.2 Evaluation of Weldments - Nondestructive Tests

In general all the weldments met the radiographic and ultrasonic requirements except for small areas of unsoundness connected with starts and stops of the EG and ES weldments which were intentionally discarded during the preparation of test specimens.

6.3 Evaluation of Weldments - Tensile and Bend Tests

All the transverse tensile and bend tests were satisfactory and the all weld metal tensile results were typical for the filler wire.

6.4 Evaluation of Weldments - Small Scale Toughness Tests

Since the primary problem of concern was with toughness degradation in the HAZ, analysis of toughness results was primarily directed toward this area. Toughness degradation for the small scale tests was considered significant based on the following:

CVN - Any value 50% below the minimum expected value for the base material as shown below:

Grade B	20 ft-lbs @ 32F
Grade CS	35 ft-lbs @ -4F
Grade EE36	20 ft-lbs @ -40F

DT - Any value 50% below the determined base material value and below 250 ft-lbs.

DWT - Any increase of NDT of more than 30F above the base material.

6.5 Evaluation of Grade B Weldments

6.5.1 Bulge Tests

The ES weldments exhibited performance equivalent to those of the SAW weldments (2077 thickness reduction). The EG weldments exhibited performance similar to those of the MM. All fractures in the EG weldments initiated in the coarse grain HAZ area with moderate plate deformation of about 9% thickness reduction. Explosion bulge test results for the EG and ES welds were considered satisfactory since they exhibited similar or better performance as compared to MMA ldments. For reference see Table 20 and Figures 53 through 55 and 64.

6.5.2 Small Scale HAZ Toughness Tests

As indicated in Table 24, CVN tests show the tendency of all the welding processes to produce some degradation in the EM. The degradation as measured by each small scale test was as follows:

	BM	MMA	SAW	EG	ES
CVN @ 2 F	42	6.3	10	8.3	10
DT @ 70F	160	240	287	27	244
DT @ 32F	87	147	70	5	26
DWT @	20F	-10F	20F	20F	30F

Values indicating significant degradation according to criteria indicated in 6.4 are underlined. The lowest average CVN values in the HAZ are indicated.

The above results indicate that the extent of toughness degradation shown by the CVN and DWT test for the EG and ES welds was not appreciably different than that for the MMA and SAW welds. The DT results at 70F indicated the toughness of ES was equivalent to the MMA and SAW weldments, while the toughness of EG was less than the MMA and SAW weldments. The DT results at 32F indicated brittleness in the base metal, however,the test values for the EG and ES weldments were lower than those of MM SAW and the base material.

6.6 Evaluation of Grade CS Weldmen

6.6.1 Bulge Tests

The ES weldments showed equivalent performance to the MMA and SAW weldments with approximately 12% thickness reduction.

The specimens from the EG weldments showed somewhat poorer performance than the other processes. Of the three specimens tested two separated and one showed about 50% separation along the weld. All fractures were initiated in the coarse grain HAZ area with moderate degrees of plate deformation ranging from 6 to 11% thickness reduction. As previously noted, the rate of heat input for the EG was significantly higher than for the ES; the former used a square butt whereas the latter had a 16 degree included angle. See Table 21 and Figures 56 and 57 and 64.

6.6.2 Small Scale HAZ Toughness Tests

As indicated in Table 25, some evidence of HAZ degradation was shown in at least one of the small scale tests for each welding process. The degradation as measured by each small scale test was as follows:

	BM	MMA	SAW	EG	ES
CVN @ -4F	110	87	68	33	42
DT @ 70F	935	1082	860	<u>160</u>	<u>240</u>
DT @ -4F	1000	<u>125</u>	558	<u>37</u>	<u>22</u>
DWT	-70F	<u>-20F</u>	-40F	<u>-10F</u>	-40F

Values indicating significant degradation according to criteria indicated in 6.4 are underlined. The average CVN values in the HAZ are indicated.

It is noted that the EG weldments which exhibited a somewhat poorer explosion bulge performance as compared to the other processes also exhibited generally lower toughness in the small scale toughness tests. In regard to the CVN test, the results of the EG and ES weldments were significantly less than base material. However, the above values are considered acceptable for Grade CS material.

6.7 Evaluation of Grade EH36 Weldments

6.7.1 Bulge Tests

The EG and ES weldments exhibited significantly less toughness than the MMA and SAW weldments. Two of the three EG specimens and two of the four ES specimns separated on the first shot along the weld in the coarse grain HAZ area as shown in Figures 65 and 66. All first shot separations exhibited less than 3% reduction in thickness. One of the two MMA and both SAW eldments were exposed to three shots and exhibited approximately 10% reduction with no visible cracks. The remaining MMA weldraent fractured on the third shot with extensive involvement of plate material in the fracture. For reference see Table 22 and Figures 58 through 60.

6.7.2 Small Scale HAZoughness Tests

The small scale toughness results shown in Table 26 indicated that the EG and ES weldments had a degraded zone in the HAZ,nd had significantly inferior toughness as compared to the MMA and SAW. The extent of degradation was as follows:

	BM	MMA	sAW	EG	ES
CVN @ -40F	62	37	41	5.5	7.0
DT @ 70F	865	625	847	70	55
DT @ -40F	108	87	105	20	7
DWT	-90F	-80F	-70F	0F	-10F

Values indicating significant degradation according to the criteria indicated in 6.4 are underlined. The lowest average CVN values in the HAZre indicated.

From the above, it appears that all of the individual small scale tests would have clearly predicted the explosion bulge results at OF in the EG and ES welds.

6.8 Evaluation of Grade ASMA203 Grade A Weldrnents

6.8.1 Bulge Tests

The specimens from the EG and ES weldments showed poorer performance than those from the MMA and SAW weldments. Each of the two specimens from the EG and ES weldments withstood single shots without evidence of any cracking; but separated along the weld in the coarse grain area of the after the second shot with approximately 57. reduction in thickness. The

MMA eldments withstood three shots with no separation and approximately 10% reduction in thickness. Fractures formed after the third shot exhibited extensive base metal tearing. The SAWweldments withstood three shots with 11% reduction, with no evidence of cracking. For reference see Table 23 and Figures 61 through 4.

6.8.2 Small Scale HAZ Toughness Tests

The small scale toughness results, as shown in Table 27, indicated that the EG and ES weldments had inferior toughness as compared to the W and SAWweldments. However, the lowest HAZ values indicated for the EG and ES welds would normally be accepted for ABS Grade EH36 sine the lowest values indicated approximate Grade EH36 base material requirements. Comparative HA values were as follows:

			BM	MMA	sAW	EG	ES
CVN	@	-40F	95	50	79	21	16
DT	@	70F	1200	1200	1130	<u>150</u>	<u>122</u>
DT	@	-40F	65	190	330	<u>5</u>	<u>25</u>
DWT			-10OF	-120F	-l10F	<u>-80F</u>	<u>-40F</u>

Values indicating significant degradation according to the criteria indicated in 6.4 are underlined. The lowest average CVN values in the HAZ are indicated. The above values indicate the lower toughness which had been evidenced in explosion bulge test was also evidenced in the CVN and DT test.

<u>6.9 Correlation of Small Scale Toughness Results with Explosion Bulge Tests</u>

The degree of consistency of small scale tests with the comparative performance observed in explosion bulge test was considered to be as follows :

Material	CVN	DT	DWT
B	+	0	+
CS	0	0	0
EH36	+	+	+
ASTM A203 Grade A	+	+	

(+) indicates a positive correlation
(-) indicates a negative correlation
(0) not definitive

The above tabulation is based on the particular temperatures selected for the referenced tests. Previous work[4] has indicated good correlation between DT and explosion bulge tests conducted at the same temperature. It is believed that a higher degree of correlation than that shown might have been achieved if DT tests had been conducted at the same temperature as the explosion bulge tests. However, as discussed in the approach, the DT tests were conducted at two temperatures only; 70F (Seee 1.4) and the temperature at which the CVN tests were carried out,

7.0 DISCUSSION

7.1 Service Experience

It should be recognized that using service experience as the evaluating criteria, MMA, SAW, EG and ES welds in Grade B steel and MM and SAW welds in Grades CS and EH36 steels have proven satisfactory in service. Accordingly, both the explosion bulge and small scale results from such welds are considered to be representative of satisfactory weldmentspro In this regard, it is well to note that Grade B steel is not employed in the most highly stressed areas of large ship hulls.

7.2 Loading Rate

In considering the significance of the test results it should be recognized that the loading rate and the extent of deformation involved in explosion bulge testing are far greater than those encountered by hull materials under the usual service conditions. Resistance of Grades B, CS, EH36 and ASTMA203 Grade A materials to fracture propagation may be adversely affected by high loading rates. Accordingly, brittle performance in the explosion bulge test at a particular test temperatre should not be considered to imply brittle performance at the same temperature under the lower loading rates of service conditions in a merchant ship structure. However, ductile performance in the explosion bulge test would imply ductile performance of a crack free weld at service conditions at the same temperature.

7.3 Test Temperature

The test temperature selected for each material for the explosion bulge tests was the most suitable for comparing performance of the welding processes. The scope of the project did not provide for evaluation at other temperatures. When evaluating weldments for a particular service condition, consideration should be given to design stress or anticipated service stress, permissible flaw size and safety factor in addition to test temperature and loading rate as mentioned in 7.2 above. In this connection it should be noted that the explosion bulge test temperature, 0F for Grades EH36 and ASTM A203 Grade A and 20F for Grade CS, is below the normally referenced 32F service temperature for merchant ships.

7.4 CVN and DT Correlation with Explosion Bulge Tests

This program was conducted using the explosion bulge test as the primary basis for establishing comparative toughness performance; small scale toughness tests were intended to provide supplemental information. However, on the basis of the correlations observed, it appears that a reasonably reliable estimate of comparative explosion bulge performance can be made on the basis of the CVN and DT HAZ toughness tests, with due consideration being given to the test temperatures used for each test.

7.5 Joint Design

Based on the difference in performance between the EG and ES weldments it is possible that the bevel joint design used for the ES weldments is more resistant to fracture propagation than the square joint design used for the EG weldments.

7.6 Heat Input

As previously discussed the major concern when using the EG and ES welding processes is the effect of the high rate of heat input on the HAZ. In evaluating the comparative performance of these two processes, it should be recognized that each may be applied with a wide range of heat input rates. Accordingly, when satisfactory results have been obtained with one of the two processes similar satisfactory results can be achieved with the other process since it is reasonable to assume that by appropriate selection of welding parameters, comparable heat inputs in the EG and ES processes can be realized to produce HAZ areas with similar microstructures and properties. In this regard the heat input rate for the EG weldments, 710,000 joules/in., as compared to the heat input rate for the ES weldments, 430,000 joules/in., may account in part for the generally poorer performance of the EG weldments. In evaluating the performance of the SAW process it should be noted that heat input for SAW welds as indicated in Table 6, is representative of the highest calculated single arc. As discussed in 1.4, it is probable that the total heat input of the triple arc technique used is somewhat additive due to the close proximity of the three arcs. (See Note 1 of Table 6).

7.7 EG and ES Welding of ABS Hull Steels and ASTM A203 Grade A

Based on the above considerations estimates of the applicability of EG and ES welding to the various grades of ABS hull steels can be made. Pertinent data related to all the various ABS hull steels are shown in Table 28.

7.7.1 ABS Grade A and B Steels

The EG and ES processes have been successfully applied to these steels and are currently used in production. Results observed in this investigation for Grade B steel indicated that degradation in HAZ properties observed in EG and ES welds was similar to that obtained with MMA and SAW.

7.7.2 ABS Grade CS Steel

High heat input processes such as ES can be used to make weldments in Grade CS steel, which exhibit tough performance at 20F, as evidenced by explosion bulge tests. The better performance of ES welds as compared to EG suggest that beveled joints and lower heat input rates (ES relative to EG as used in this investigation) could be significant factors in determining the joint toughness inweldments made with high heat input processes. It is reasonable to assume that EG weldments in Grade CS steel with toughness characteristics equivalent to the ES welds, might be attained if the joint design and heat input rate for the two processes were comparable.

7.7.3 ABS Grade DS Steel

On the basis of the results obtained withthe Grade CS steel, it appears that the EG and ES processes may be applicable to Grade DS steel for special application service. In this regard, it should be noted that the required composition for the Grades DS and CS steels is identical and the only difference between Grades DS and CS steels is that the former is not normalized and is usually not provided in thickness over 1-3/8 in. The principal degradation of toughness in EG and ES welds in Grade CS steel has been observed in the grain coarsened recrystallized area of the HAZ. Since the required chemical composition for Grades DS and CS are identical the toughness properties of the recrystallized area of the HAZ in EG and ES welds would be expected to be similar for both grades.

7.7.4 ABS Grade D Steel

Additional work would be required to assess the applicability of the processes to Grade D steel. Because of the higher carbon and lower manganese limits of Grade D steel as compared with Grades DS or CS steel, it might be expected that toughness of the HAZ of a EG or ES weld in Grade D steel, especially if it were semi-killed, could approximate those observed with the Grade B steel. The potential of the processes to produce joints with toughness adequate for Grade D applications appear less probable with Grade D than with the Grade DS.

7.7.5 ABS Grade E Steel

As indicated in Table 28, Grade E chemistry requirements encompass those of Grade CS, but has a broader range of chemical composition than Grade CS. In view of the permissible higher carbon and lower manganese of the Grade E as compared to Grade CS, lower HAZ toughness may be found in EG and ES welds for some chemistry combinations of Grade E. Until such time as the effects of the higher carbon and lower manganese content of the Grade E steel can be assessed, the results reported herein for Grade CS steel should not be considered applicable to Grade E steel.

7.7.6 AIM Grade EH36 Steel

The results of small scale tests showed significant toughness degradation in the HAZ of the high heat input EG and ES welds; the extent of degradation was significantly less for the MMA and SAW. In addition, the explosion bulge test performance of EG and ES welds at OF were significantly inferior to comparable MMA and SAW welds. Since this investigation was primarily conducted to develop comparative EG and ES data with the commonlyusesMMA and SAW welding processes, information was not developed relativeto explosion bulge performance at higher temperatures, such as the 20F temperature used for the explosion bulge evaluation of Grade CS steel. In view of the relatively good explosion bulge results observed for Grade CS welds at 20F, evaluation of EG and ES welds in

Grade EH36 steel at a 20F test temperature or possibly higher should be considered. On the basis of the prelimiary results, applicability of the EG and ES processes for services requiring high toughness in the HAZ would require additional effort to develop improved techniques, such as lowering the heat input, modifying the joint design, establishing more restrictive chemistry requirements for higher strength steels or developing alloys with less tendency for HAZ degradation in high heat input welding.

7.7.7 ABS Grades AH36, DH36, AH32, DH32 andEH32

In regard to Grade EH32 steel the comments of 7.7.6 are considered applicable since the material is furnished according to the same specified chemistry and heat treatment. Concerning AH and DH higher strength steel grades, the toughness properties of the HAZ of the Grade EH36 is likely to approximate that for these other higher strength steels since they have the same chemical composition limits. However, evaluation of toughness at temperatures higher than those appropriate for Grade EH steel should be considered since their CVN weld and base material properties are less restrictive. Accordingly, potential application of the EG and ES processes to AH and DH steels would be dependent upon an assessment of the toughness as evaluated by small scale tests and the toughness required for the particular application.

7.7.8 ASTM A203 Grade A Steel

The results of small scale tests showed significant toughness degradation in the HAZ of the high heat input EG and ES welds, but not to the same extent as for Grade EH36 steel. Similarly, the explosion bulge performance of EG and ES welds in ASTM A203 Grade A steel was inferior to comparable MMA and SAW welds, but superior to the EG and ES welds in Grade EH36 steel. For the same reasons indicated in 7.7.6 above, evaluation of a low alloy steel such as ASTM A203 Grade A at 20F should also be considered particularly since the lowest CVN HAZ values obtained approximate Grade EH36 base material requirements. (See 6.8.2).

8.0 CONCLUSIONS

on the basis of this investigation and the results obtained, the following conclusions have been made.

8.1

HAZ toughness degradation occurred to some extent for all materials considered in this investigation. Evidence of various degrees of HAZ toughness degradation, as measured by CVN, occurred in localized areas forMMAnd SAW as well as for EG and ES welds.

8.2

In the case of EG and ES welds, maximum CVN HAZ toughness degradation was observed at or within 3 mm of the fusion line. (See Figures 23 through 26). In the case of MM and SAW welds, maximum HAZ toughness degradation was observed at a variety of locations and no general conclusion concerning location can be drawn.

8.3

In the case of the Grade B steel, EG and ES welds exhibited performance in explosion bulge tests essentially similar to the W and SAW welds. The present ABS practice of not requiring CVN HAZ toughness tests for ordinary applications is considered valid.

8.4

In the case of Grade CS steel, ES welds exhibited explosion bulge performance equivalent to the MMand SAW welds, although the HAZ of ES welds evidenced somewhat lower toughness than MM and SAW welds in the small scale toughness tests. EG welds exhibited a greater degree of HAZ toughness degradation as compared to ES welds, in both small scale and explosion bulge tests. The significant differences between the EG and ES welds were that EG welds had a square joint, and ES welds a beveled one, and a higher rate of heat input was used for EG welds.

8.5

The use of Grade DS steel is considered preferable to Grade D for EG and ES weldments because of the more restrictive chemistry of DS.

8.6

When Grade CS steel is used in special application areas, uninterrupted welding of the side shells of normal strength steel with high heat input processes such as the EG 02 ES processes is feasible. This conclusion may or may not be applicable to Grade E in view of its less restrictive chemical composition. On the basis of the results reported herein and the lack of more definitive criteria CVN toughness tests of the HAZ should be carried out for EG and ES welds in Grades CS and E steel during procedure testing.

8.7

Welding of Grade EH36 higher strength steel by high heat input EG and ES processes resulted in significant HAz degradation as measured by small scale toughness tests. EG and ES welds exhibited significantly less toughness than the MMA and SAW welds in explosion bulge tests.

8.8

ASTM A203 Grade A, 2¼% nickel alloy steel, welded by high heat input EG and ES processes exhibited somewhat better HAZ toughness and large scale explosion bulge performance than similar welds in Grade EH36 steel. However, EG and ES welds in this alloy exhibited significantly lower toughness than those welded by the lower heat input MMA and SAW processes.

8.9

Results of CVN and DT toughness tests have shown reasonable correlation with explosion bulge performance, when due consideration is given to selection of test temperature.

8.10

CVN tests have been shown capable of indicating abrupt changes in toughness in EG and ES welds within distances as small as approximately 2 mm.

8.11

In general for Grades CS, EH36 andASTMA203 Grade A steels the high heat input, EG and ES welds exhibited greater HAZ toughness degradation than the conventional MMA and SAW welds.

8.12

The performance of ES welds (410,000 joules/in.) using beveled joints was better than EG welds (710,000 joules/in.) using square joints.

8.13

SAW welds made with the tandem triple arc technique generally exhibited superior toughness in small scale and explosion bulge tests as compared to MMA, EG and ES welds. Only one SAW weld exhibited cracking during explosion bulge testing. However,the cracking was restricted to the bulge area and the specimen remained intact as illustrated in Figure 57.

8.14

When high heat input welding processes such as EG or ES are used for special applications in important areas, the retention of adequate HAZ toughness should be verified by small scale tests, such as CVN test. However, in view of the results obtained with the Grade CS steel, the extent of small scale toughness testing of EG or ES welds in this steel may be minimized or eliminated, if sufficient data is accumulated to verify that the small scale results obtiained herein are consistently obtained in production.

9.0 FUTURE WORK

The work reported herein was exploratory in nature and no attempt was made to cover all facets. However, results have indicated several areas of information which should prove helpful to developing the technology to extend use of high heat input processes such as EG and ES welding in shipbuilding. Table 29 indicates the amount of available base material and weldments remaining from this program. From this remaining material the additional tests indicated in 9.1, 9.2, 9.4 and 9.5 are proposed to resolve some unanswered questions which became evident by this investigation.

9.1

Conduct DT tests of the weld and HAZ for each grade of material at the same temperature used for explosion bulge testing to obtain a better estimate of the value of DT tests in predicting explosion bulge test results. These tests can be readily prepared and tested from remaingwehlments.

9.2

Determine the degree of improvement in explosion bulge properties of EG and ES weldments in Grade EH36 and ASTM A203 Grade A material which can be obtained by use of procedures using lower heat input rates and modified joint designs than those used in the subject investigation. Should improvement be significant, consideration of this approach for application of EG and ES welding of Grade EH36 steel or other higher strength steels in special application areas may be advisable. This effort would require making additional test welds in Grade EH36 and ASTM A203 Grade A from remaining available material for preparation of explosion bulge tests.

9.3

Anale existing literature for guide lines as to the factors which could be used in selecting a candidate hull material equivalent to Grade EH36 strength and toughness which would exhibit minimum tendencies for HAZ toughness degradation. The potential applicability of this material should thenbe verified by conducting appropriate toughness tests Of the HAZ of EG and ES welds in the material. If successful, the approach could have a significant impact on extending the applicability of EG and ES welds in shipbuilding. This effort would require basic research, literature search, making additional test welds and preparation and testing of large and small scale toughness tests in various higher strength steels. A related benefit of this investigation would be its pertinence to the problems relating to the maintenance of HAZ toughness in the welding of inner hull and other parts of ship structures of LNG and LPG gas tankers where service temperatures of hull steels may be in the OF to -50F range.

9.4

Conduct explosion bulge tests of EG and ES welds in Grades EH36 andASTM A203 Grade A at 32F to indicate performance at approximate service temperature conditions. This effort would require making additional test welds in Grade EH36 from remaining available material for preparation of explosion bulge tests.

9.5

Conduct explosion bulge tests for all welds in Grade CS and MMA and SAW welds in Grade EH36 at temperatures lower than 20F and OF respectively. Similar materials are being used in the OF to -50F temperature range in LNG ship structures, and information on explosion bulge performance of MMA and SAW weldments could provide important information on the toughness characteristics of these weldments. Data on EG and ES welds in Grade CS steels could provide information relative to the applicability of these processes to this service temperature range. This effort would require making additional test welds in Grades CS and EH36 from remaining available material for preparation of explosion bulge tests.

TABLE 1- DEPOSITION DATA ON VERTICAL BUTT WELDS HULL STEEL PLATE (1)

Welding Process	EG	Es (2)	M A	GMA
Joint Design (in.)	Square Butt with 11/16 gap	Square Butt with 1 gap	Double V with 1/8 gap	Double V with 1/8 gap
Plate Thickness (in.)	1	l½	1	1
Length of Weld (ft.)	50	20	50	50
Electrode Size (in.)	1/8	1/8	5/32	3/64
Estimated Deposition Rate (lb. /hr.)	30	40	2.60	6.5
Range of Heat Inputs (Kilojoules/in.)	600-900	700-1000	30-70	30-70
Approximate Arc Time (hr.)	5.3	2.75	35	14
Assumed Range of Operation(%) Factors(3)	60-80	60-80	20-40	30-60
Estimated Total The (hr.) (Arc Time/OperationFactor)	8.8-6.6	4.6-3.4	175-87	46-23

1. Table 1 reflects data in general agreement with the 6th Edition AWS Welding Handboook, Section 1 Chapter 7.

2. AWS Welding Handbook did not list data on the ES welding process for thicknesses under 1½ in. and over 20 ft. in length.

3. Operation factor represent the percentage of the work day spent in actual welding time (arc time).

TABLE 2 - TYPICAL HAZ CHARPY V-NOTCH VALUES FROM
SHIPYARD EG AND ES PROCEDURE QUALIFICATION TESTS

Process	ES	ES	ES	EG	ES	ES	EG	ES
ABS Grade	A	C	D	D	D	Cs	Cs	DH36
Thickness (in.)	1¼	1¼	1 3/8	1¼	2	1 3/8	1¼	13/16
Heat Treatment	As rolled	As rolled	Norm.	As rolled	Norm.	Norm.	Norm.	Norm.
Test Temperature (F)	32	32	32	32	32	-4	-4	-4
CVN Results(ft-lbs)								
Weld	38	29	94	45	46	33	26	50
Fusion Line		46		36	47	81	31	
1 mm		67				32	41	9
2 mm	10							
3 mm		103	45	100		26	44	29
5 mm		74				74	97	72
7 mm		106				90	134	
10 mm		1-						70
Base Material Long.	25		165	47	180			72

TABLE 3 - WELDING PARAMETERS ON PRELIMINARY TEST

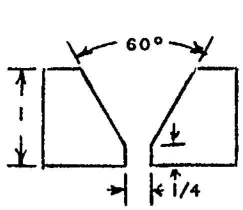
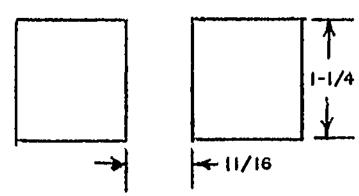
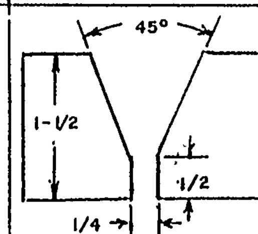
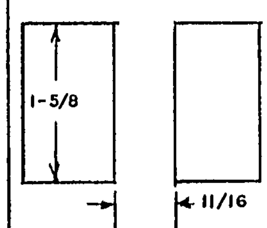
Welding Method	ES	EG	EG	EG	ES	EG
Steel	B	CH	EH36	EH36	ASTM A516 Gr.70	ASTM A203 Gr.A
Specimen No.	K80-E	K50-B	K50-A	K50-C	K82-A	K61-B
Wire (in.)	3/32 Linde 29S	1/16 Avacor 6709	1/16 Avacor 6709	1/16 Avacor 6709	3/32 Linde MC-70	1/16 Avacor 6709
Shielding Gas	-	80-20 A-CO_2	80-20 A-CO_2	80-20 A-CO_2	-	80-20 A-CO_2
Flux	Linde 124	-	-	-	Linde 124	-
Current (amp.)	350	355	355	355	425	375
Voltage	38	37.5	37.5	37.5	44	39
Feed Speed (in./min.)	-	350	350	350	-	380
Arc Speed (in./min.)	1.75	1.06	1.06	1.06	1.20	0.90
Heat Input (Joules/in.)	456,000	623,740	623,740	623,740	935,000	975,000
Joint Design (in.)						

TABLE 4 - MECHANICAL PROPERTIES AND CHEMICAL COMPOSITION OF MATERIAL EVALUATED IN PRELIMINARY TESTS

Steel	B(1)	CH (2)	EH	EH	ASTM A516Gr.70 (3)	ASTM A203 Gr. A
Specimen No.	K80-E	K50-B	K50-A	K50-c	K82-A	K61-B
Y.P. (psi)	33,000	60,500	56,500	57,600	45,000	47,000
T.S. (pS)	60,200	83,700	84,000	82,500	78,000	72,300
El.(%) in 2 in.	36.0	32.0	32.0	32.0	34.0	34.0
Heat Treatment	As Rolled	Normalized	Normalized	Normalized	Normalized	Normalized
Thickness (in.)	1	1 ¼	1 ¼	1 ¼	1 ½	1 5/8
C	0.21	0.25	0.22	0.20	0.28	0.14
Mn	0.80-1.10	1.08	0097	0.89	0.85-1.20	0.51
Si	0.35	0.28	0.32	0.32	0.15-0.30	0.18
P	0.04	0.015	0.017	0-.018	0.035	0.014
S	0.04	0.020	0.022	0.024	0.04	0.022
Ni						2.35

1. Actual composition not available. Composition limits from ABS Rules listed.
2. Grade CH hull steel 1969 ABS Rules.
3. Actual composition not available. Composition limits from ASTM A516 Gr. 70 listed.

TABLE 5 - PRELIMINARY CHARPY V-NOTCH IMPACT TEST. VALUES ON E.G. AND E.S. SMALL SCALE WELDMENTS

Steel	B	CH	EH	EH	AsTM A516-GR.70	ASTM A203 GR. A
Welding Method	ES	EG	EG	EG	ES	EG
Specimen No.	K80-E	K50-B	K50-A	K50-c	K82-A	K61 -B
Test Temp. (F)	32	-22	-40	-40	-20	-40
CVN (ft-lb)						
Weld	58.0	26.0	22.3	20.6	9.7	21.0
Fusion Line	65.7	8.5	11.8	35.3	11.7	37.0
l m m	22.3	8.5	9.0	27.0	14.7	42.0
3 m m	55.3	9.0	12.8	8.5	19.4	53.0
5 m m	101.0	71.0	41.6	7.3	36.5	52.0
7 m m	163.0	93.0	80.1	31.8	50.8	82.0
Base Metal Long.	19.7	126.0	59.5	49.3	32.0	45.0

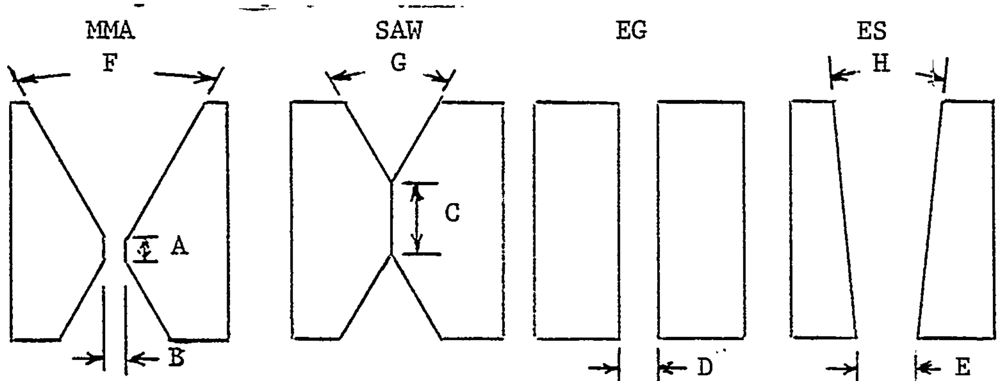
TABLE 6 - WElDING PARAMETERS FOR THE LARGE SCALE WELDMENTS

Steel	ABS Grade B(1)	ABS Grade Cs (1¼)	ABS Grade EH36 (1¼)	ASTM A203 Grade A(1¼)
M M A				
Electrode Size (in.)	5/32	1/8	1/8	1/8
Electrode Type	6011	7018	8018-C3	8018-C1
Voltage	27-31	21-23	21-23	21-23
Current (Amp .)	130-140	145-155	145-155	145-155
Travel Speed (in./min.)	3.5	3.0	3.0	3.0
Approx. Heat Input (joule/in.)	66,900	66,000	66,000	66,000
sAW (Triple Arc) (1)				
Filler Metal	RACO 120	RACO 130	RACO 130	LINDE MI 88
Wire Size (in.)	3/16	3/16	3/16	3/16
Flux	LINCOLN 860	LINDE 0091	LINDE 0091	LINDE 124
Voltage	32-46	32-46	32-46	32-46
Current (Amp.)	800-1250	850-1250	850-1250	850-1250
Travel Speed (in./mine)	35	30-35	30-35	30-35
Approx. Heat Input (2) (Joule/in.)	63,600	79,000	79,000	79,000
EG				
FIller Metal	AIRCO A608	AIRCO AVACOR 6709	AIRCO AVACOR 6709	AIRCO AVACOR 6709
Wire Size (in.)	1/8	5/64	5/64	5/64
Shielding Gas	80/20 A-C02	80/20 A-C02	80/20 A-C02	80/20 A-C02
Gas Flow (CFH)	160	160	160	160
Current (Amp.)	420	480	480	480
Voltage	38	37	37	37
Travel Speed (in./min.)	1.5	1.5	1.5	1.5
Approx. Heat Input (joule/in.)	638,000	710,000	710,000	710,000

TABLE 6 (CONTINUED) WELDING PARAMETERS FOR THE LARGE SCALE WELDMENTS

Steel	ABS Grade B	ABS Grade CS	ABS Grade EH36	ASTM A203 Grade A
<u>ES</u>				
Filler Metal	LINDE 29S	LINDE MI-88	LINDE MI-88	LINDE MI-88
Wire Size (in.)	3/32	3/32	3/32	3/32
Flux	LINDE 124	LINDE 124	LINDE 124	LINDE 124
Current (Amp.)	380-390	380-390	380-390	380-390
Voltage	36-38	36-38	36-38	36-38
Travel Speed (in./min.)	2.25	2	2	2
Approx. Heat Input (joule/in.)	380,000	432,000	432,000	432,000

JOINT DESIGN



	A (in.)	B (in.)	C (in.)	D (in.)	E (in.)	F (deg.)	G (deg.)	H (deg.)
1 in. Thickness	1/8	1/8	3/8	11/16	1/2	60	70	22
1¼ in. Thickness	1/8	1/8	3/8	11/16	1/2	60	70	16

(1) The electrode spacing between the first and second arc was 2.75 in. and the electrode spacing between the second and third arc was 0.75 in.

(2) Highest calculated single arc heat input.

TABLE 7 - CHEMICAL COMPOSITION OF FILLER METALS USED ON LARGE SCALE WELDMENTS (TYPICAL)

	C	Mn	Si	Ni	Mo	Cr
E6011[1]	0.08	0.35	0.11			
E7018[1]	0.04	0.65	0.55			
E8018-c3([1])	0.04	0.90	0.40	1.0	0.20	
E8018-C1(1)	0.05	0.97	0.33	2.32		
RACO 120	0.11	0.45	0.03			
RACO 130	0.11	1.87	0.07	0.96	0.48	
AIRCO A608	0.10	1.78	0.82		0.41	
AVACOR 6709	0.044	1.5	0.31	2.03	0.48	0.12
LINDE 29s	0.11	1.00	0.45			
LINDE MI 88	0.04	1.65	0.35	1.5	0.40	0.25

1. Typical deposited weld metal from manufacturer’s Handbook.

TABLE 8 - EXPLOSION BULGE TEST TO ESTABLISH CHARGES AND STAND OFF DISTANCES

Grade	Thickness (in.)	Test Temp. (F)	Stand Off Distance (in.)	Charge (lb.)	Shot No.	% Reduction A	% Reduction B	Depth of Bulge (in.) A	Depth of Bulge (in.) B	Remarks
B	1	30	17	7	1	4.0	3.7	2.3	2.2	No cracks
					2	8.9	10.1	3.3	3.2	No cracks
					3	17.3	18.5	4.4	4.4	No cracks
					4	-	-	-	-	Plate shattered
EH36	1¼	-20	19	12	1	2.8	3.2	1.2	1.2	No cracks
					2	6.2	5.9	2.1	2.1	No cracks
					3	9.7	8.6	2.7	2.8	No cracks

TABLE 9 - CRACK STARTER EXPLOSION BULGE TEST RESULTS

Grade	Thick-ness (in.)	Temp. (F)	Shot No.	% Reduction		Longest Crack from(in) Apex	Total	Remarks
B	1	80	1	3.4	3.1	to edge	18.8	Plate separated on A, side and cracked almost to edge B Side.
B	1	120	1	6.3	6.5	6.8	13.2	Cracks did not extend into hold down area.
			2					Plate separated
CS	1¼	0	1	2.5	1.3	8	15.5	Crack from center 7.5 IN into A side and 8 in.into B side. Crack also 7.2in. into B side. Crack into hold down area on A side. :
CS	1¼	20	1	3.6	4.0	0.2		Tear across crack starter bead does not enter base material.
			2	6.0	7.6	6		Plate cracks in 7 directions from weld bead. Cracks from 4.8in. to 6 in length.

TABLE 10 - CHEMICAL COMPOSITION OF BASE MATERIAL[1]

Material	C	M	P	S	Si	Ni	Cb	V	Al	Cr	Mo	Cu
Grade B												
Required	0.21	0.80-1.10	0.04	0.04	0.35							
Product Analysis	0.21	0.92	0.007	0.018	0.01							
Grade CS												
Required	0.16	1.00-1.35	0.04	0.04	0.10-0.35							
Product Analysis	0.15	1.13	0.008	0.022	0.28							
Grade EH36												
Required	0.18	0.90-1.60	0.04	0.04	0.10-0.50	0.40	0.05	0.10	0.065	0.25	0.08	0.35
Product Analysis	0.18	1.44	0.009	0.020	0.27	-	0.036[2]	-	0.043[2]	0.17[2]	0.005[2]	0.03[2]
ASTM A203 Grade A												
Required	0.17	0.70	0.035	0.040	0.15-0.30	2.10-2.50						
Product Analysis	0.14	0.64	0.002	0.008	0.23	2.07[3]						

Notes:
(1) Single values of the required compositions are maximums.
(2) Ladle analysis from steel manufacturer.
(3) Acceptable on product analysis.

TABLE 11 - MECHANICAL PROPERTIES OF BASE MATERTAL[1]

Grade	B	CS	EH36	ASTM A203 Grade A
Thickness (in.)	1	1¼	1¼	1¼
Deoxidation Practice	Semi-Killed	Killed fine grain	Killed fine grain	Killed fine grain
Heat Treatment	As-Rolled	Normalized	Normalized	Normalized
Ultimate Tensile (ksi)	60.2	64.5	73.7	71.0
Yield (ksi)	32.7	43.6	51.3	52.1
Elong. % in 8 in.	34	32	30	30
CVN (ft-lbs)[2]	42 @ 32 F	110 @ -4 F	62@ -40 F	95 @ -40 F
DT (ft-lbs)[3]	87 @ 32 F	1000 @ -4 F	108 @ -40 F	65 @ -40 F
DWT-(NDT)	20 F	-70 F	-90 F	-100 F

Notes: (1) Material purchased to 1973 ABS Rules.

(2) Average of at least three tests.

(3) Average of at least two tests.

TABLE 12 - MECHANICAL PROPERTIES OF WELDMENTS
ON ABS GRADE B MATERIAL

Welding Method	MMA	SAW	EG	ES
Transverse Tensile(1) (psi)	66,400	65,300	63,800	66,500
Guided Side Bends(180°)	OK	OK	OK	OK
All Weld Metal (psi)				
Tensile	73,000	72,500	94,600	72,500
Yield Point	59,400	55,600	74,500	50,600
% Elong. 2 in.	24	29	22	30
% RA	66	69	62	69
CVN Tested @ 32F (2) (ft-lbs)				
¢ Weld	66.3	85.0	32.6	44.7
Fusion Line	74.3	69.0	11.6	10.0
1 MM	87.3	82.0	8.3	37.0
3 MM	88.3	53.0	28.0	83.7
5 mm	22.6	78.0	53.3	74.7
7 mm	6.3	10.0	65.6	16.0
9 mm	6.3	15.0	46.3	33.3
Base Metal	42.0	42.0	42.0	42.0
DT Tested @ 70F (3) (ft-lbs)				
¢ Weld	642	1200	102	206
HAZ	240	287	27	244
Base Metal	160	160	160	160
DT Tested @32F (3) (ft-lbs)				
¢ Weld	232	425	28	73
HAZ	147	70	5	26
Base Metal	87	87	87	87
DWT - (NDT)				
¢ Weld	-30 F	0 F	-30 F	-10 F
HAZ	-10 F	+20 F	+20 F	+30 F
Base Metal	+20 F	+20 F	+20 F	+20 F

Notes:
1. Average of 2 tests.
2. Average of 3 tests.
3. Average of 2 tests.

TABLE 13 - MECHANICAL PROPERTIES OF WELDMENTS ON ABS GRADE CS MATERIAL

Welding Method	MMA	SAW	EG	ES
Transverse Tensile (1) (psi)	70,000	70,800	69,700	70,100
Guided Side Bends (180°)	OK	OK	OK	OK
All Weld Metal (1) (psi)				
Tensile	81,500	96,400	92,600	103,800
Yield Point	71,400	81,400	76,500	81,800
% Elong. 2in.	26	22	24	24
% RA	76	64	65	62
CVN Tested @ -4F (2) (ft-lbs)				
℄ Weld	46.6	58.0	37.1	46.6
Fusion Line	81,5	90.0	37.0	57.8
1 mm	87.1	69.0	33.0	42.3
3 mm	94.8	89.0	51.5	73.5
5 mm	117.0	74.0	116.0	106.5
7 mm	96.5	71.0	125.0	128.8
9 mm	96.6	68.0	128.0	81.6
Base Metal	110.0	110.0	110.0	110.0
DT Tested @ 70F (3) (ft-lbs)				
℄ Weld	105 (4)	1062	817	800
HAZ	1082	860	160	240
Base Metal	935	935	935	935
DT Tested @ -4F (3) (ft-lbs)				
℄ Weld	10 (4)	185	310	437
HAZ	125	558	37	22
Base Metal	1000	1000	1000	1000
DWT - (NDT)				
℄ Weld	-70 F	-70 F	-80 F	-90 F
HAZ	-20 F	-40 F	-10 F	-40 F
Base Metal	-70 F	-70 F	-70 F	-70 F

Notes:
(1) Average of 2 tests.
(2) Average of 6 tests.
(3) Average of 2 tests.
(4) Average of 4 tests. The first set of DT had much lower values than expected for a E7018 electrode especially in view of the CVN and DWT indicated. DT retests revealed similar values. Reasons for these unusually low DT values could not be established.

TABLE 14 - MECHANICAL PROPERTIES OF WELDMENTS ON ABS GRADE EH 36 MATERIAL

Welding Method	MMA	SAW	EG	ES
Transverse Tensile [1] (in.)	80, 790	80,300	76,200	81,900
Guided Side Bends (180)	OK	OK	OK	OK
All Weld Metal [1] (psi)				
Tensile	95,200	100,200	98,700	109,400
Yield Point	84,900	91,800	80,500	77;000
% Elong. 2 in.	23	22	22	22
% R A	64	66	64	64
CVN Tested @ -40F [2] (ft-lbs)				
¢ Weld	42.6	38.0	23.5	27.0
Fusion Line	52.6	41.0	5.5	76.0
1 mm	47.8	52.0	12.6	7*O
3 mm	51.9	46.0	15.5	15.6
5 mm	39.6	51.0	99.8	87.0
7 mm	37.0	42.0	96.1	92.0
9 mm	59.9	49.0	106.3	100.0
Base Metal	62.0	62.0	62.0	62.0
DT Tested @ 70F [3] (ft-lbs)				
¢ Weld	1070	1047	292	312
H A Z	615	847	70	55
Base Metal	865	865	865	865
DT Tested @ -40F [3] (ft-lbs)				
¢ Weld	50	55	42	46
HAZ	87	105	20	7
Base Metal	108	108	108	108
DWT - (NDT)				
¢ Weld	-60 F	-70 F	-90 F	-70 F
HAZ	-80 F	-70 F	O F	-10 F
Base Metal	-90 F	-90 F	-90 F	-90 F

Notes:
1. Average of 2 tests.
2. Average of 6 tests.
3. Average of 2 tests.

TABLE 15 - MECHANICAL PROPERTIES OF WELDMENTS
ON ASTM A203 GRADE A MATERIAL

Welding Method	MMA	SAW	EG	ES
Transverse Tensile (1) (psi)	74,000	73,300	72,900	73,500
Guided Side Bends (180°)	OK	OK	OK	OK
All Weld Metal (1) (psi)				
Tensile	96,200	89,400	92,900	106,500
Yield Point	84,400	80,900	76,800	79,800
% Elong. 2 in.	23	24	24	25
% RA	63	62	64	68
CVN Tested @ -40F (2) (ft-lbs)				
℄ Weld	55.1	53.0	25.6	51.0
Fusion Line	99.2	87.0	21.0	16.0
1 mm	50.4	106.0	26.0	19.0
3 mm	89.0	104.0	50.8	46.0
5 mm	69.1	100.0	88.5	108.0
7 mm	87.0	83.0	118.6	157.0
9 mm	87.1	79.0	123.5	151.0
Base Metal	95.0	95.0	95.0	95.0
DT Tested @ 70F (3) (ft-lbs)				
℄ Weld	1200	1200	545	807
HAZ	1200	1130	150	122
Base Metal	1200	1200	1200	1200
DT Tested @ -40F (3) (ft-lbs)				
℄ Weld	125	336	127	210
HAZ	190	330	5	25
Base Metal	65	65	65	65
DWT - (NDT)				
℄ Weld	-120 F	-80 F	-110 F	-90 F
HAZ	-120 F	-110 F	-80 F	-40 F
Base Metal	-100 F	-100 F	-100 F	-100 F

Notes:
1. Average of 2 tests.
2. Average of 6 tests.
3. Average of 2 tests.

TABLE 16 - HARDNESS SURVEY ACROSS WELDS ON ABS GRADE B MATERIAL
ROCKWELL "B"

Process(1)	MMA		SAW		EG		ES	
Specimen No.	B1	B2	B5	B6	B3	B4	B7	B8
Base Metal	70.0	69.4	69.6	67.2	69.4	70.0	67.5	71.6
11 mm from F.L.	79.0	75.0	76.0	74.1	71.8	71.1	71.5	72.3
9 mm from F.L.	79.7	77.1	75.5	74.1	73.0	74.5	74.5	73.5
7 mm from F.L.	80.5	77.0	75.3	73.1	74.3	74.3	75.0	76.1
5 mm from F.L.	81.3	76.6	77.0	74.5	75.3	75.0	76.0	77.8
3 mm from F.L.	79.3	77.1	78.6	75.5	77.6	77.3	77.0	79.6
1 mm from F.L.	82.1	82.0	79.8	77.1	79.3	78.6	79.0	82.6
F. L.	84.3	84.8	81.8	80.1		84.6	83.8	85.5
Weld Metal	86.5	87.2	80.8	81.4	93.6	94.5	83.6	84.6
F. L.	84.5	84.3	78.8	79.6	78.6	83.5	80.3	82.5
1 mm from F.L.	83.8	80.3	76.8	78.6	76.5	79.0	79.1	84.3
3 mm from F.L.	79.8	79.0	74.3	78.1	73.8	78.0	77.3	81.0
5 mm from F.L.	80.0	78.7	72.5	75.6	71.8	75.8	76.0	78.8
7 mm from F.L.	80.5	78.7	73.1	75.1	71.6	74.6	75.6	77.0
9 mm from F.L.	79.8	77.6	74.6	76.1	70.8	74.8	73.0	74.0
11 mm from F.L.	78.0	75.8	74.6	76.5	69.3	73.5	73.1	72.8
Base Metal	72.8	77.0	66.1	69.2	64.4	69.5	69.5	70.5

(1) Specimens macroetched to determine location from fusion line (F.L.

TABLE 17 - HARDNESS SURVEY ACROSS WELDS ON ABS GRADE CS MATERIAL
ROCKWELL "B "

Process[1]	MMA		SAW		EG		ES	
Specimen No.	cl	C2	C5	c6	C3	C4	C7	C8
Base Metal	74.2	74.2	74.6	74.3	72.5	74.1	74.6	74.4
11 mm from F.L.	78.5	79.5	79.8	80.3	75.1	75.8	77.6	76.5
9 mm from F.L.	80.0	81.3	80.1	80.1	75.8	77.0	79.5	77.8
7 mm from F.L.	82.0	83.1	80.6	81.0	76.3	77.3	79.5	78.3
5 mm from F.L.	83.1	84.6	81.5	81.8	77.8	78.5	80.6	80.0
3 mm from F.L.	85.0	85.3	83.1	84.0	81.5	82.1	84.6	83.5
1 mm from F.L.	87.6	87.6	85.1	85.5	83.3	84.3	87.6	86.1
F.L.	89.6	89.0	94.1	91.5	90.3	93.5	95.8	95.6
weld Metal	87.0	86.0	95.9	94.5	91.3	95.2	98.0	97.9
F.L.	88.8	89.0	85.5	87.3	88.0	85.6	88.3	87.3
1 mm from F.L.	87.5	88.0	85.3	84.3	81.0	84.0	87.8	85.1
3 mm from F.L.	89.8	89.3	82.3	82.0	77.8	80.8	83.8	81.8
5 mm from F.L.	86.0	88.1	80.5	80.3	77.1	77.8	80.0	79.1
7 mm from F.L.	85.0	86.6	79.3	80.3	76.3	77.6	79.8	77.8
9mm from F.L.	83.1	84.8	80.0	80.5	75.3	77.8	78.3	77.6
11 mm from F.L.	78.5	83.0	80.1	80.5	74.3	76.6	77.0	76.6
Base Metal	74.1	74.1	74.5	74.8	72.5	75.3	75.5	73.9

(1) Specimens macroetched to determine location from fusion line (F.L.).

TABLE 18 - HARDNESS SURVEY ACROSS WELDS ON ABS GRADE EH36 MATERIAL
ROCKWELL "B"

Process(1)	MM/i		SAW		EG		ES	
Specimen No.	El	E2	E5	E6	E3	E4	E7	E8
Base Metal	81.4	80.4	82.8	82.4	80.0	80.6	82.5	81.9
11 mm from F.L.	83.8	82.8	89.5	87.0	81.8	84.1	84.0	83.5
9 mm from F.L.	85.6	84.0	88.8	87.5	82.0	84.6	85.6	84.6
7 mm from F.L.	87.0	85.8	89.3	87.1	83.0	86.5	87.0	86.0
5 mm from F.L.	85.6	87.6	91.8	88.6	87.3	91.0	90.0	90.6
3 mm from F.L.	90.0	88.5	93.5	91.0	91.0	93.8	94.6	94.1
1 mm from F.L.	93.0	92.1	97.1	96.6	93.8	94.8	96.3	95.0
F.L.	95.8	98.6	98.5	97.1	95.1	95.8	97.5	97.3
Weld Metal	94.3	94.0	99.4	98.3	96.4	95.4	99.4	99.0
F.L.	96.6	96.0	97.1	98.0	94.0	94.5	95.8	94.6
1 mm from F.L.	97.5	90.6	97.0	95.6	93.3	94.0	95.8	95.1
3 mm from F.L.	90.0	87.6	92.6	93.0	90.0	92.3	94.1	93.5
5 mm from F.L.	89.0	86.3	89.8	91.3	84.6	86.1	89.5	88.8
7 mm from F.L.	87.8	85.3	89.1	88.5	82.3	84.0	85.8	85.6
9 mm from F.L.	85.6	84.0	88.3	88.0	81.6	83.6	85.5	84.3
11 mm from F.L.	84.1	82.6	87.8	87.8	81.8	82.6	84.1	82.8
Base Metal	82.0	81.0	81.7	83.1	80.8	81.3	82.4	82.0

(1) Specimens macroetched to determine location from fusion line (F.L.).

TABLE 19 - HARDNESS SURVEY ACROSS WELDS ON ASTM A203 GRADE A MATERIAL
ROCKWELL "B"

Process (1)	MMA		SAW		EG		ES	
Specimen No.	Al	A2	A5	A6	A3	AL+	A7	A 8
Base Metal	78.0	78.5	78.1	77.4	77.9	78.8	76.4	80.0
11 mm from F.L.	81.0	81.1	79*5	81.3	79.3	80.0	78.8	81.5
9 mm from F.L.	82.1	82.8	81.5	81.5	80.0	81.6	79.8	82.6
7 mm from F.L.	83.8	83.3	82.3	83.5	79.4	81.5	80.3	83.0
5 mm from F.L.	84.3	85.1	82.3	83.8	81.1	80.8	80.8	83.3
3 mm from F~L.	86.8	86.3	84.5	86.5	84.6	83.5	84.0	85.6
1 mm from F.L.	89.3	89.5	89.0	89.3	87.1	88.0	85.5	90.0
F.L.	92.6	92.0	92.3	92.6	90.3	92.8	93.5	94.3
Weld Metal	94.2	94.6	91.8	93.6	92.7	93.1	98.5	97.5
F.L.	89.6	89.0!	88.3	90.0	88.1	88.5	89.8	90.0
1 mm from F.L.	87.1	87.1	86.5	88.1	86.8	87.3	87.8	89.8
3 mm from F.L.	85.1	85.8	85.0	84.8	85.1	82.8	84.1	86.5
5 mm from F.L.	84.0	85.0	82.6	82.8	81.0	82.3	80.6	84.0
7 mm from F.L.	82.5	82.6	81.8	81.1	80.1	81.5	79.5	83.1
9 mm from F.L.	81.1	87.0	80.5	80.6	79.8	80.6	79.3	82.6
11 mm from F.L.	80.1	80.8	80.1	80.8	79.8	79.3	79.1	81.0
Base Metal	77.2	79.0	77.9	77.1	78.2	80.1	75.9	79.5

(1) Specimens macroetched to determine location from fusion line (F.L.).

TABLE 20 ABS GRADE B EXPLOSION BULGE TEST RESULTS

Specimen No.	Welding Method	Test Temp F	Shot No.	% Thickness Reduction A	% Thickness Reduction B	Depth of Bulge (in.) A	Depth of Bulge (in.) B	Longest Crack (in.)	Remarks
B-1	MMA	30	1						Plate broke into 3 pieces.
B-1A	MMA	120	1	4.0	4.6	2.3	2.3		No visible cracks
			2	10.9	10.7	3.4	3.4		Surface tears in weld bead
			3					13	4 cracks from center into base material.
B-2	MMA	120	1	4.7	4.5	2.3	2.3		No visible cracks
			2	10.6	9.6	3.4	3.4		No visible cracks
			3					6.75	Entire center area brolce out with 9 cracks radiating from center areas.
B-3	EG	120	1	4.2	3.8	2.3	2.2		No visible cracks
			2	9.3	10.3	3.4	3.4		No visible cracks
			3					7.5	Center area broke out with 7 cracks radiating from center area.
B-4	EG	120	1	4.0	3.7	2.3	2.3		No visible cracks
			2	8.8	10.4	3.3	3.7	Plate separated	Plate separated along weld
B-5	SAW	120	1	4.4	4.1	2.3	2.2		No visible cracks
			2	9.8	10.4	3.4	3.4		No visible cracks
			3	19.9	19.2	4.2	4.2	6.5	Shallow crack along weld
B-6	sAW	120	1	4.5	4.1	2.2	2.2		No visible cracks
			2	10.2	10.4	3.4	3.4		No visible cracks
			3	19.2	20.3	4.2	4.2	2.5	Shallow crack along weld
B-7	Es	120	1	3.1	3.0	2.2	2.2		No visible cracks
			2	8.4	8.9	3.4	3.4	l 75	Crack on compression side in base material
			3	15.8	19.6	4.3	4.5	4.5	Crack in plate on compression side penetrated to tension side near edge of die.
B-8	ES	120	1	3.0	3.7	2.3	2.4		No visible cracks
			2	8.2	9.4		3.4		No visible cracks
			3	17.6	20.7	4.2	4.3		No visible cracks

TABLE 21 ABS GRADE CS EXPLOSION BULGE TEST RESULTS

Specimen No.	Welding Method	Test Temp. F	Shot No.	% Thickness Reduction A	% Thickness Reduction B	Depth of Bulge (in.) A	Depth of Bulge (in.) B	Longest Crack (in.)	Remarks
C-1	MMA	20	1	3.4	3.2	1.4	1.5		No visible cracks
			2	8.6	7.8	2.6	2.6		No visible cracks
			3	13.5	13.4	3.3	3.4		No visible cracks
C-2	MMA	20	1	2.5	2.4	1.3			No visible cracks
			2	7.3	7.1	2.5	1.3		No visible cracks
			3	12.1	10.9	3.3	3.3		No visible cracks
C-3	EG	20	1	2.3	2.3	1.4	1.4		No visible cracks
			2	5.8	6.1	2.7		Plate separated	Plate separated along weld with crack radiating from center area into base material 6.5in long.
C-3A	EG	20	1	4.2	5.2	1.8	1.7		No visible cracks
			2	9.4	8.8	2.8	2.8		No visibl,e trucks
			3					13.2	Large piece broke out B side at center and a large piece almost broke out of A side at center. Separation along weld almost to edge on both sides. Cracks into base material from center area 4.5 in. & 1.5 in. long.
C-4	E.G	20	1	2.6	2.7	1.5	1.5		No visible cracks
			2	6.2	6.7	2.6	2.6		No visible cracks
			3	9.4	12.2	-	3.5	Plate separated	Plate separated along weld with 2 craclcs radiating from center area into base material 4.5in. & 5.4 in. long.
C-5	SAW	20	1	3.5	3.0	1.6	1.5		No visible cracks
			2	8.5	7.6	2.6	2.6		No visible cracks
			3	13.6	12.6	3.4	3.4		No visible cracks
C-6	sAW	20	1	2.7	2.5	1.2	1.2		No visible cracks
			2	6.5	7.4	2.4	2.4		No visible cracks
			3	10.8	12.4	3.4	3.5	17.8	Crack in base metal across weld
C-7	Es	20	1	3.7	3.2	1.4			No visible cracks
			2	7.4	7.9	2.6	1.5		No visible cracks
			3	12.3	12.7	3.3	3.3		No visible cracks
C-8	Es	20	1	3.0	3.5	1.4	1.4		No visible cracks
			2	6.9	7.3	2.6	2.5		No visible cracks
			3	11.6	12.2	3.2	3.2		No visible cracks

TABLE 22 ABS GRADE EH36 EXPLOSION BULGE TEST RESULTS

Specimen No.	Welding Method	Test Temp. OF	Shot No.	% Thickness Reduction A	B	Depth of Bulge(in.) A	B	Longest Crack (in.)	Remarks
E-1	MMA	0	1	3.5	3.9	1.4	1.4	-	No visible cracks
			2	6.6	7.4	2.3	2.4	-	No visible cracks
			3						Entire center area blew out
E-2	MMA	0	1	2.9	3.0	1.3	1.3	-	No visible cracks
			2	7.2	6.7	2.4	2.3	-	No visible cracks
			3	10,3	10.4	3.0	3.0	-	No visible cracks
E-3	EG	0	1	0.78	0.63	108	107	Plate separated	Plate separated along weld on B side to near center across weld and along A side of weld to edge. Section of weld broke out of plate. Crack into base material from weld 2 in. long.
E-3A	EG	0	1	2.6	2.2	2.3	1.8	Plate separated	plate separated along weld. Crack into base material from center area 3.2Ln. long.
E-4	EG	0	1	3.5	3.0	1.3	1.3	-	No visible craclcs
			2	6.5	6.7	2.3	2.3	-	No visible cracks
			3	9.3	9.1	2.9	2.9	-	No visible cracks
E-5	sAW	0	1	3.1	3.0	1.3″	1.3		No visible cracks
			2	6.8	6.7	2.3	2.2		No visible craclcs
			3	10.1	10.2	3.0	3.0		No visible cracks
E-6	SAW	0	1	2.8	3.1	1.1	1.1		No visible cracks
			2	6.3	6.8	2.2	2.2		No visible cracks
			3	10.1	10.2	3.0	3.0		No visible craclcs
E-7	Es	0	1	3.2	3.6	1.3	1.3		No visible craclcs
			2	6.4	7.2	2.3	2.3		No visible craclcs
			3		10.2	-	-	5.5	Large piece broke out of center area. SeparMiOn along weld A side right of center from hole to 1.8 in.of left edge along the weld part of this distance. 5 craclcs radiating from center area into base material with longest 5.5 in.
E-7A	ES	0	1	3.3	3.6	1.4	1.3	10	Plate separated along weld from right of center of left edge. Craclc across the weld into base material 8in.long. 3 other cracks from center area into base material 3.2 to 3.5 in. long.
E-8	ES	0	1	2.9	2.7	1.5	1.5	Plate separated	Plate separated along weld with 2 snmll cracks into base maberial from weld.
E-8A	ES	0	1	1.4	1.1	2.0	1.7	Place separated	Plate separated along weld.

TABLE 23 ASTM A203 GRADE A EXPLOSION BULGE TEST RESULTS

Specimen No.	Welding Method	Test Temp. (F)	Shot No.	% Thickness Reduction A	% Thickness Reduction B	Depth of Bulge (in.) A	Depth of Bulge (in.) B	Longest Crack (in.)	Remarks
A-1	MMA	0	1	4.2	4.4	1.9	1.8		Ho visible cracks
			2	8.3	8.9	2.8	2.8		NO visible crackS
			3	10.8	12.9			11	Piece on right side almost broken out of plate. Cracks radiating from center area into base material.
A-2	MMA	0	1	3.1	3.0	1.5	1.5		No visible cracks
			2	7.2	7.1	2.5	2.5		No visible cracks
			3	10.1	9.6			8.5	2 pieces almost broken out of center area. Cracks radiating from center area into base material longest 8.5 in.
A-3	EG	0	1	2.4		1.6	1.6		No visible cracks
			2	5.6	4.5			Plate separated	Plate separated along weld from left to center on A side then across weld into base material on B side 5.5in. & then back along weld to edge. Cracks radiating from center area in base material 2.8 into 9 in. long.
A-4	EG	0	1	2.8	3.1	1.6	2.7		No visible cracks
			2	5.0	5.2	1.6		Plate separated	Plate separated along weld. Cracks radiating from center area into base material 3 in. and 6.8 in. long.
A-5	sAW	0	1	3.3	3.5	1.5	1.5		No visible cracks
			2	7.6	7.0	2.6	2.5		No visible cracks
			3	11.0	11.0	3.3	3.1		No visible cracks
A-6	sAW	0	1	3.3	3.3	1.5	1.4		No visible cracks
			2	7.4	7.5	2.6	2.5		No visible cracks
			3	10.3	10.9	3.2	3.2		No visible cracks
A-7	Es	0	1	2.6	2.6	1.7	1.7		No visible cracks
			2	4.8	5.8			Plate separated	Plate separated along weld. Cracks radiating from center area into base material 5.2in.long.
A-8	Es	0	1		2.6	1.7	1.7		No visible cracks
			2	4.7	4.9	3.4	2.9	Plate separated	Plate separated along weld from edge to left of center on side B then across weld and along weld on side A to other edge. Crack A side along weld from center to left 2.8in. then into base material 4.5in. 3 cracks radiating into base material from center area 5.8in. to 6.5 in. long.

TABLE 24 - ANALYSIS OF TEST RESULTS ON GRADE B WELDMENTS

Process	Small Scale Toughness Test Results			Bulge Tests
	@ 32 F	@ 70,32 F	DWT Base Material(NDT)20 F	@ 120 F
MMA	Low HAZ values of 6.3 ft-lb @ 7 to 9mm	240 ft-lb in HAz better than base material @ 70 F	Similar to base material	3 shots with 10.5% reduction and base material cracks.
sAW	Low HAZ values of 10 ft-lbs @ 7 tO 9mm	Similar to MMA	Similar to W	3 shots with 19.5 % reduction and no craclcs
EG	Low HAZ values of 8.3 ft-lbs @ fusion line	Brittleness @ 70 F	Similar to MM	Inferior to W
ES	Low HAZ values of 10 ft-lbs @ fusion line	Similar to MMA	Similar to W	Similar to SAW with 18.5% reduction and no cracks
Summary	All weldments had low toughness zone	EG inferior	All weldments similar	EG inferior

TABLE 25 - ANALYSIS OF TEST RESULTS ON GRADE CS WELDMENTS

Process	Small Scale Toughness Test Results			Bulge Tests
	CVN @ - 4 F	@ 70 & -4F	DWT Base Material(NDT)-70 F	@ 2 0 F
M M A	No significant HAZ degradation from base material of 110 ft-lbs,	No significant HAZ degradation @ 70 F	Rise in NDT temperature to -20 F	No craclcs after 3 shots with 12.5% reduction
SAW	Similar HAZ to MMA	Similar to MMA	Rise in NDT temperature to -40 F	Similar to MMA
EG	Lower HAZ values to 33 ft-lbs @ 1 mm	Low HAZ toughness @ 7 0 F	Highest rise in NDT temperature to -10 F	Inferior to W & SAW
ES	Lower HAZ values of 42 ft-lbs @ 1 mm	Toughness @ 70 F	Rise in NDT temperature to -40 F	Similar to W & SAW
Summary	EG and ES somewhat lower values	EG inferior	EG highest NDT	EG inferior

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TABLE 26 - ANALYSIS OF TEST RESULTS ON GRADE EH36 WELDMENTS

Process	Small Scale Toughness Test Results			Bulge Tests
	@ -40F	@ 70 & -40 F	DWT Base Material (NDT)-90 F	@ O F
MMA	Somewhat lower HAZ values of 37 ft-lbs @ 7 mm compared to base metal of 62 ft-lbs	Somewhat lower values @ 70 F of 615 to 865 ft-lbs of base material	Similar to base material	1077 reduction after 3rd shot
sAW	Similar HAZ to MMA	No degradation	Similar to MMA	Similar to MMA with no cracKs
EG	Low HAZ values of 5.5 ft-lbs @ fusion line	Brittleness in HAZ @70F	Significant rise in NDT temperature to O F	Significantly inferior to MMA
ES	Low HAZ values of 7.0 ft-lbs @ 1 mm	Brittleness in HAZ @ 70 F	Significant rise in NDT temperature to -10 F	Significantly inferior to MMA
Summary	EG and ES low values	EG and ES brittle	EG and ES high NDT	EG and ES inferior

TABLE 27 - ANALYSIS OF TEST RESULTS ON ASTM A203 GRADE WELDMENTS

1

Process	Small Scale Toughness Test Results			Bulge Tests
	CVN @ -40 F	DT @70 & -40F	DWT Base Material (NDT)-100 F	@ 0 F
MMA	Somewhat lower HAZ values of 50 ft-lbs @ 1 mm compared to 95 ft-lbs base material	No degradation @ 70 F	No significant degradation	Craclcs propagating into base material on 3rd shot 10% reduction
sAW	No significant degradation	Similar to MMA	Similar to MMA	Similar to W with no cracks
EG	Lower HAZ values of 21 ft-lbs. @ fusion line	Low HAZ toughness @ 70 F	Rise in NDT temperature of HAZ tO -80 F	Inferior to W
ES	Lower H&Z values of 16 ft-lbs @ fusion line	Low HAZ toughness @ 70 F	Highest rise in NDT temperature of HAZ to -40 F	Inferior to W
Summary	EG and ES lower values	EG and ES inferior	EG highest NDT	EG and ES inferior

TABLE 28 - REQUIREMENTS FOR ABS GIWDE HULL STEELS

	Ordinary Strength (58-71 ksi Tensile)					Higher Strength (71-90 ksi Tensile)		
	B	D	E	DS	Cs	AH	DH	EH
Deoxidation Practice	Semi-lcilled	Killed fine grain	Killed fine grain	Killed fine grain	Killed fine grain	Semi-lcilled or Killed	Killed fine grain	Killed fine grain
Heat Treatment	As-rolled	Normalized over 1 3/8(i,n.)	Normalized	Normalized over 1 3/8(in.)	Nomnalized	Normalizing dependent on thickness and micro-alloying		Normalized
Chemical Comp. (1)								
C	0.21	0.21	0.18	0.16	0.16		0.18	
Mn	0.80-1.10	0.70-1.40	0.70-1.35	1.00-1.35	1.00-1.35		0.90-1.60	
P	0.04	0.04	0.04	0.04	0.04		0.04	
S	0.04	0.04	0.04	O*O4	0.04		0.04	
Si	0.35	0.10-0.35	0.10-0.35	0.10-0.35	0.10-0.35		0.10-0.50	
Al		0.02-0.06	0.02-0.06	0.02-0.06	0.02-0.06		0.060	
Ni							0. 04	
Cr							0.25	
Mo							0.08	
Cu							0.35	

Note : (1) A single value indicates a maximum.

TABLE 29 - REMAINING WELDMENTS AND BASE MATERIAL AVAIIABLE FOR FURTHER TESTS

Grade	Welding Process	No. of Explosion Bulge Welded Specimens 20 X20(in.)	Inches of Weld in Smaller Pieces with Width of 20 inches	Base Plate Material (in.)
B	MMA	1	0	80 X 96
	sAW	2	14	
	EG	2	18	
	ES	2	0	
CS	MMA	2	16, 14	80 X 96
	sAW	2	9, 12	
	EG	1	18	
	ES	2	0	
EH36	MMA	2	22, 14	80 X 96
	SAW	2	0	
	EG	1	20, 13	
	ES	0	14	
AsTM A203Gr. A	MMA	2	7, 14	80 X 96
	SAW	2	10	
	EG	2	9	
	ES	2	9, 3	

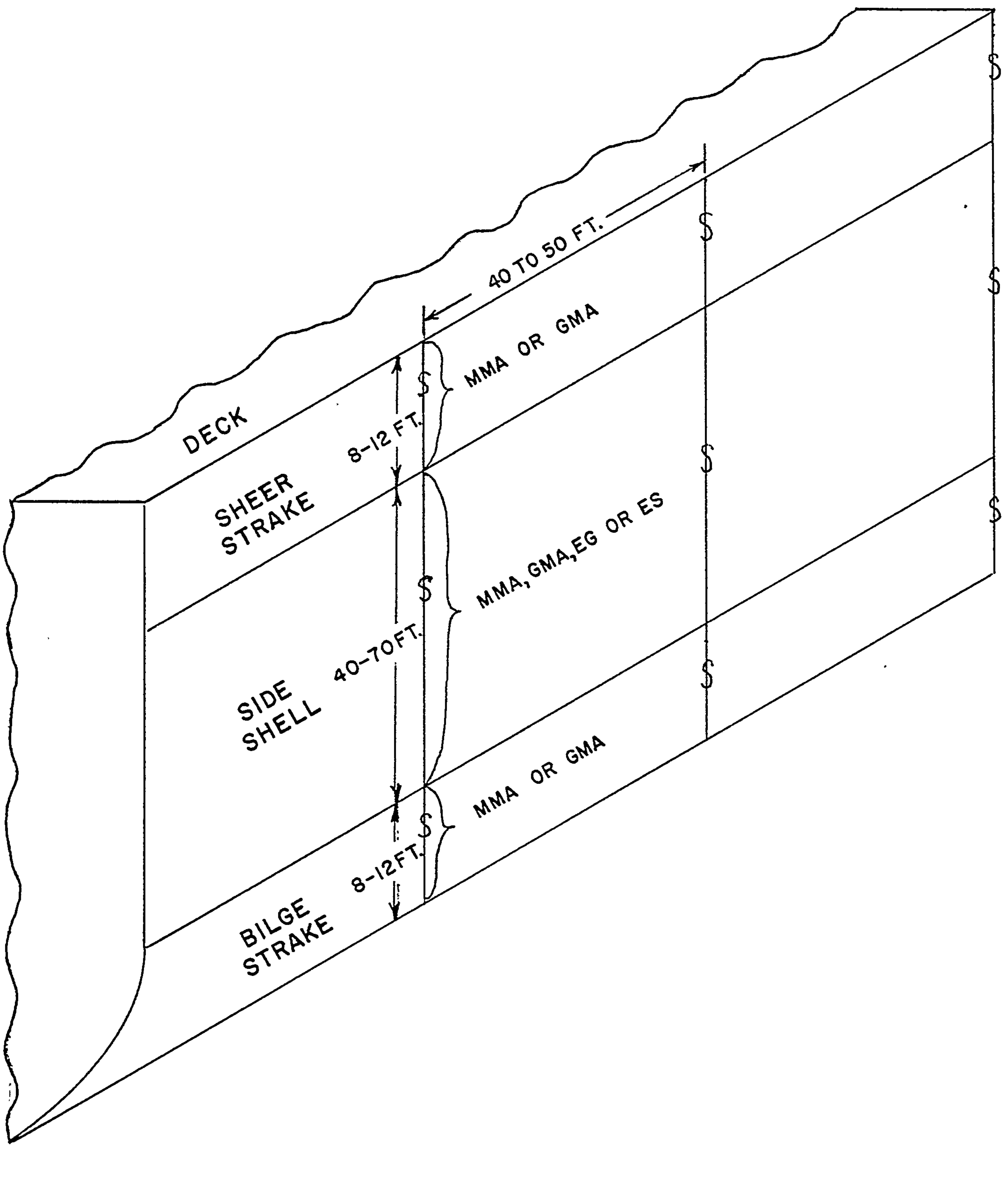
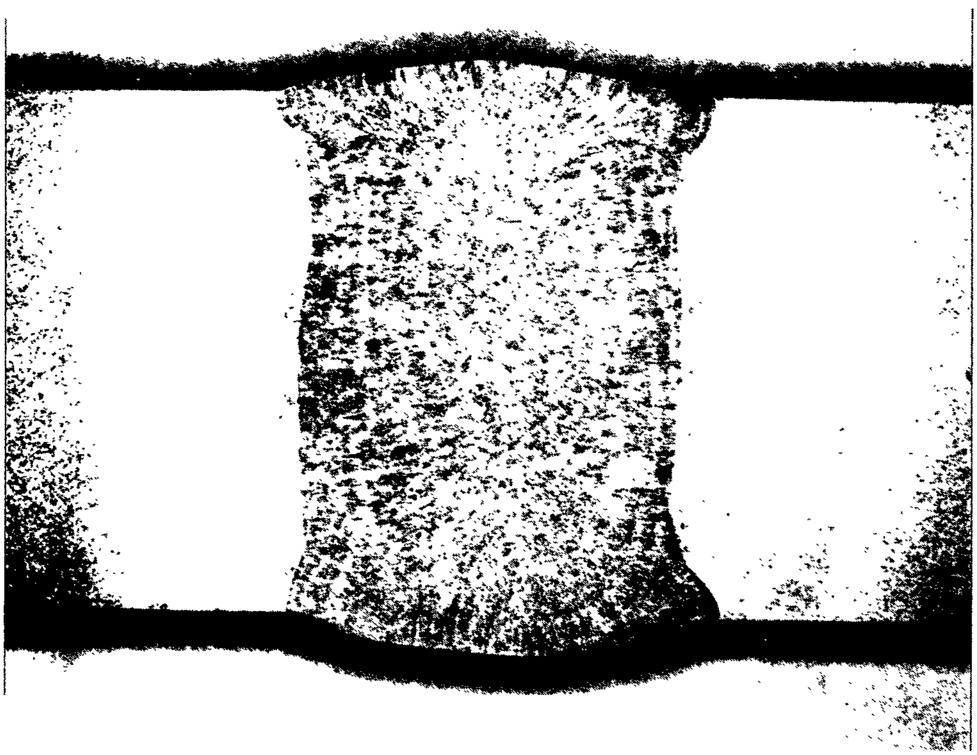
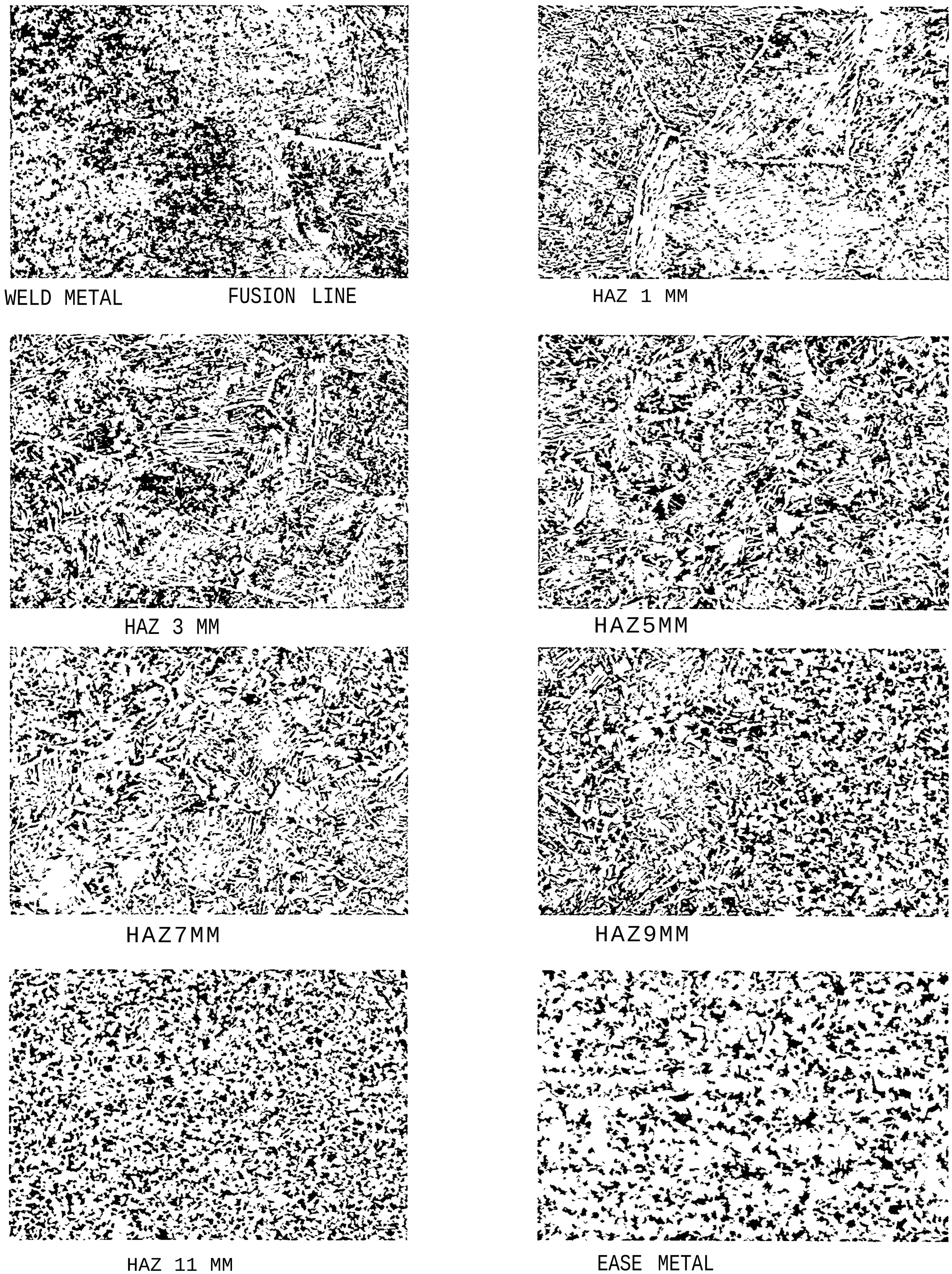


FIGURE 1 - TYPICAL SIDE SHELL BUTT SHOWING CURRENTLY USED WELDING PROCESSES



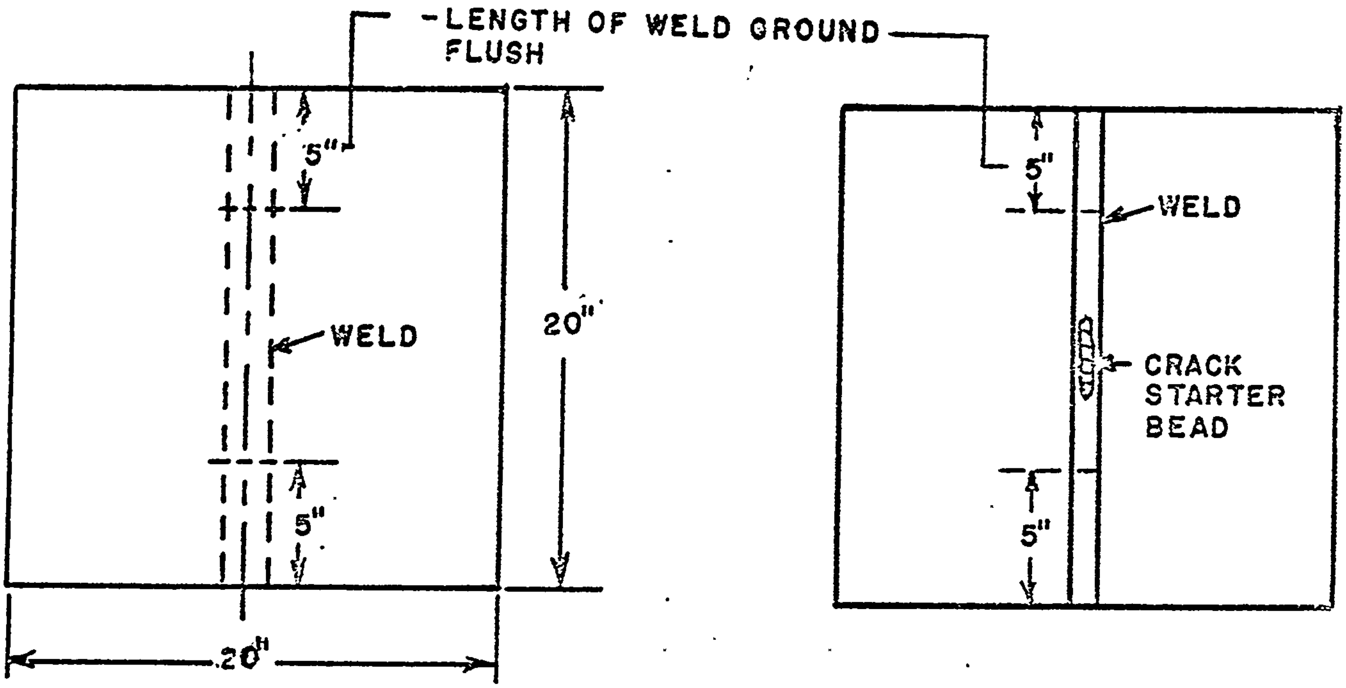
(10% NITAL ETCH - 2X)

FIGURE 2 - PHOTOMACROGRAPH OF TYPICAL EG WELD IN NORMALIZED HULL STEEL (ABS GRADE CH)



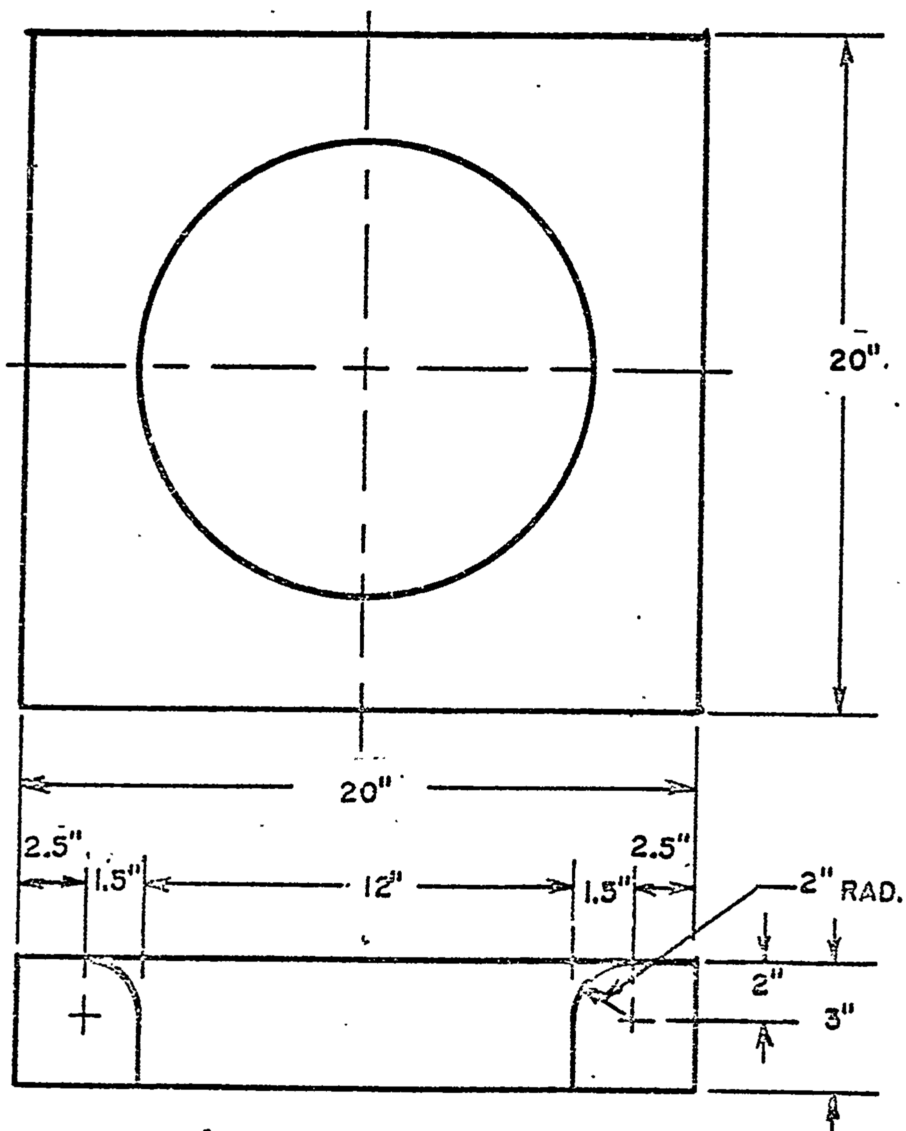
(2% NITAL ETCH - 100 x)

FIGURE 3 - PHOTOMICROGRAPHS OF TYPICAL EG WELD IN NORMALIZED HULL STEEL
(ABS GRADE CH)

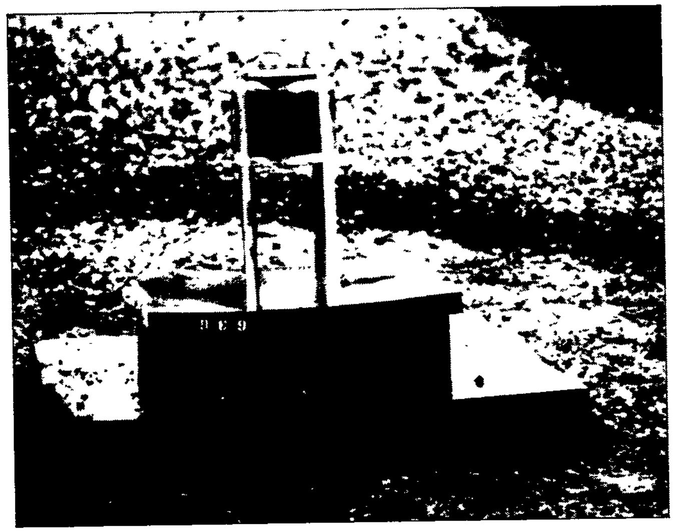


EXPLOSION BULGE

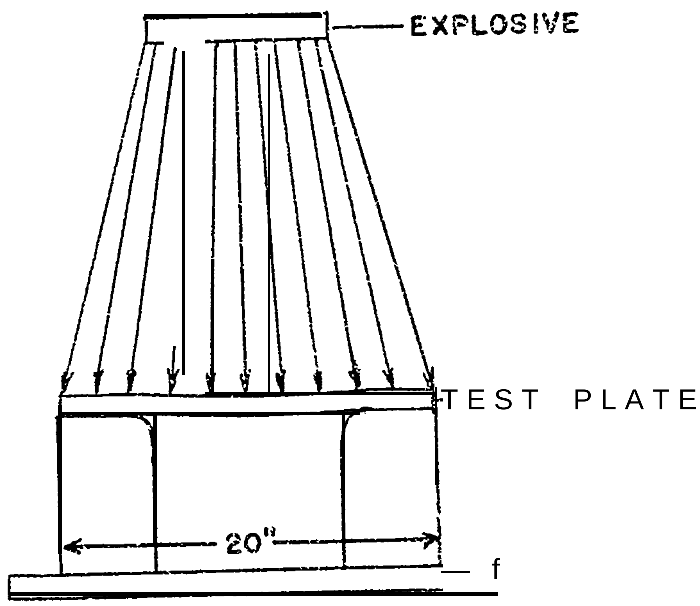
CRACK STARTER



DIE

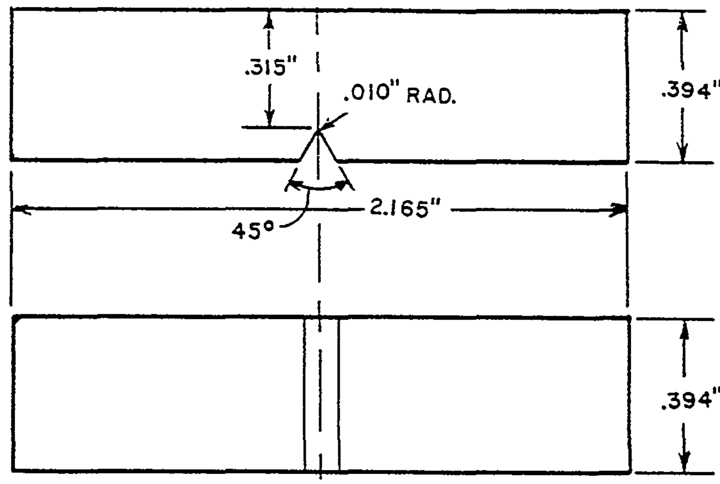


PHOTOGRAPH OF EXPLOSIVE CHARGE, SPECIMEN AND DIE

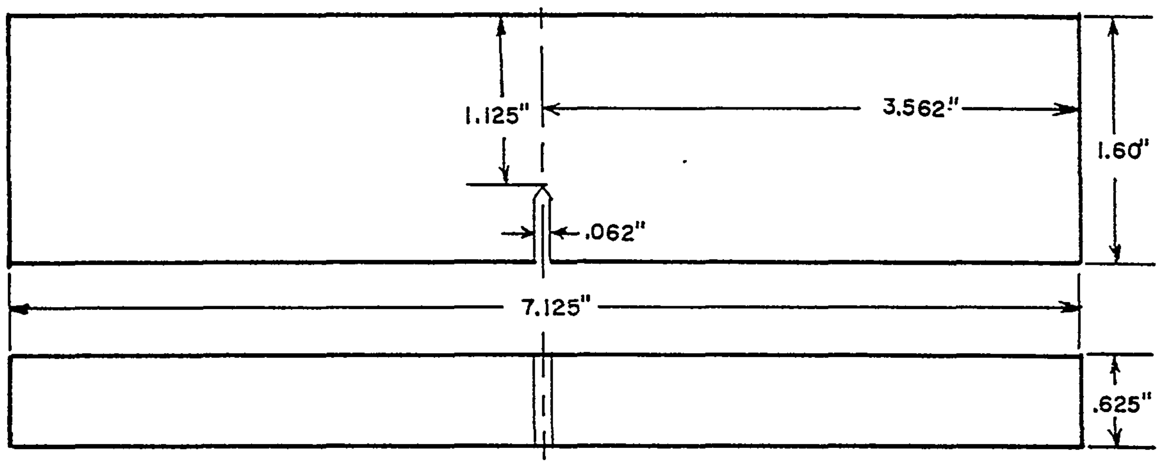


SCHEMATIC DRAWING OF EXPLOSION BULGE TEST

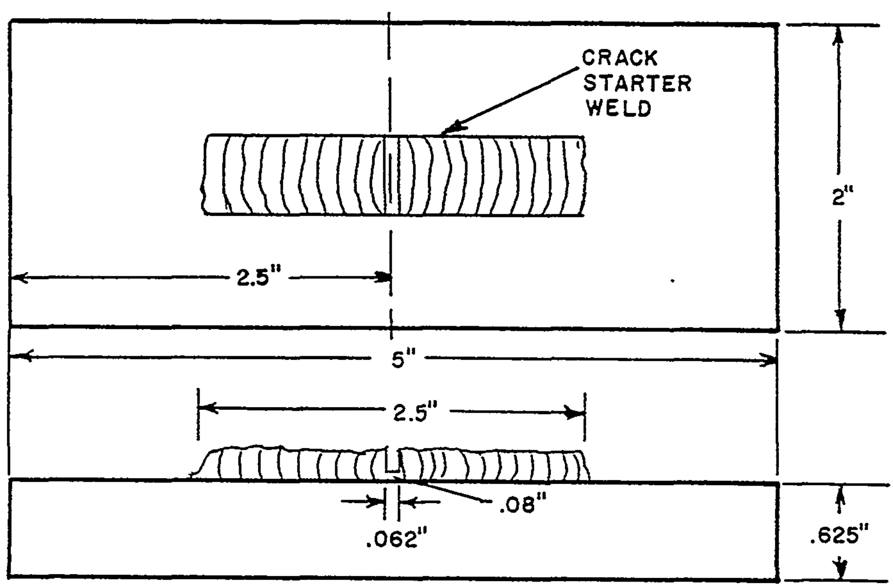
FIGURE 5 - TYPICAL EXPLOSION BULGE SET-UP



CHARPY V-NOTCH



DYNAMIC TEAR



DROP WEIGHT

FIGURE 6 - SMALL SCALE TOUGHNESS SPECIMENS

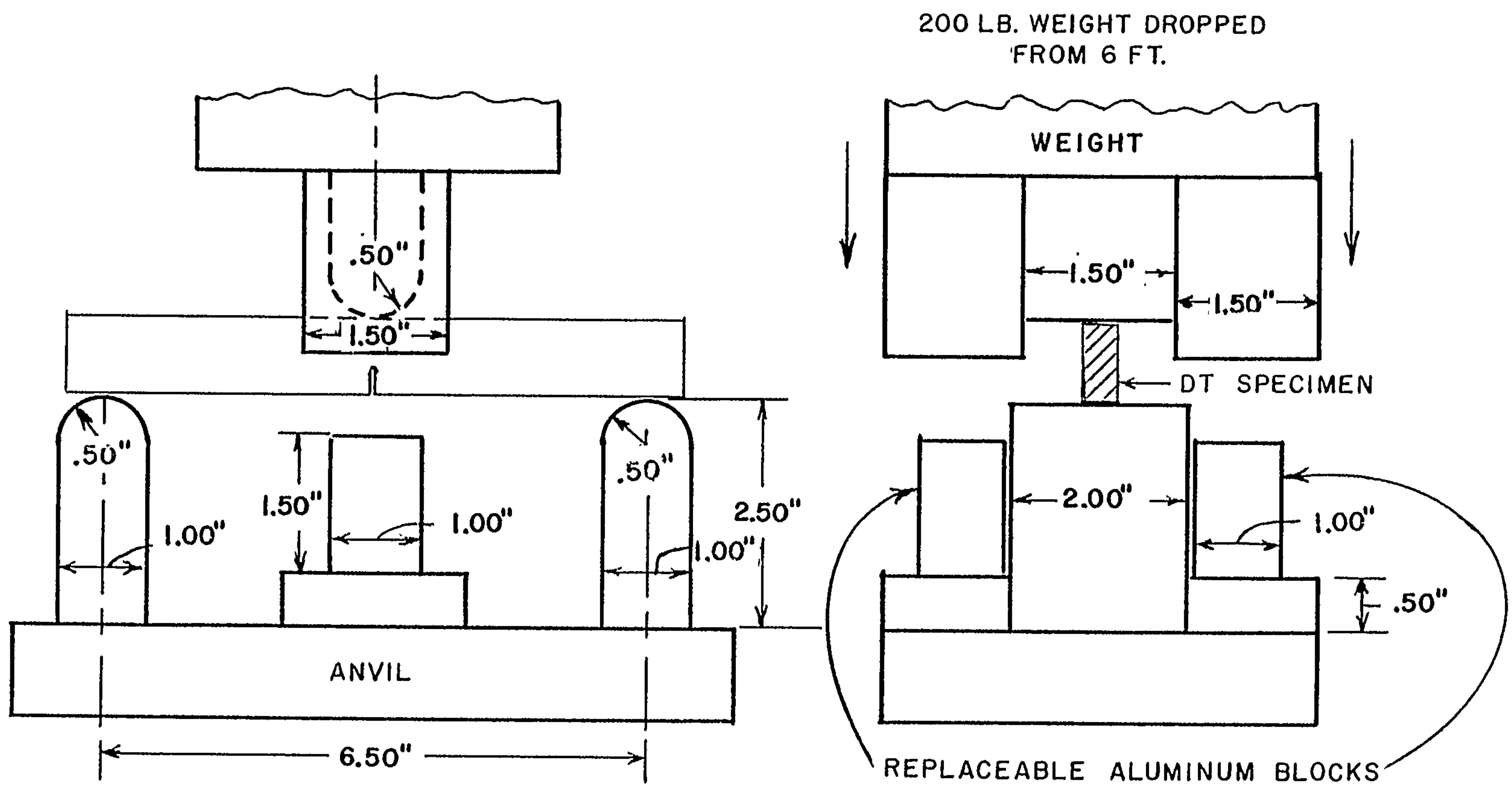
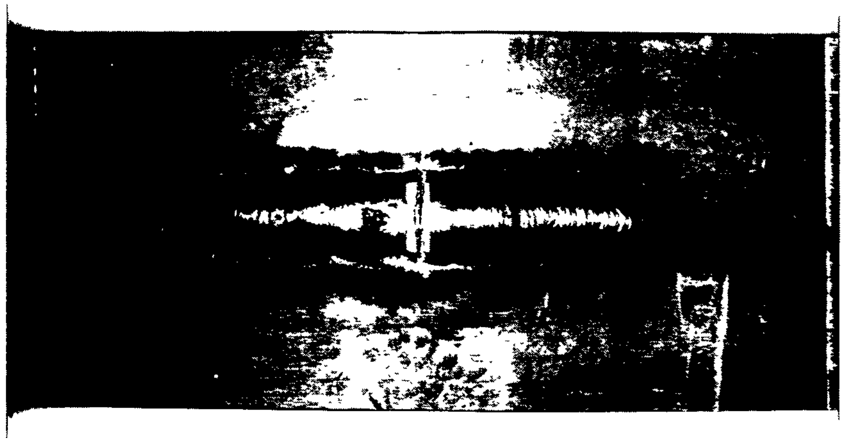
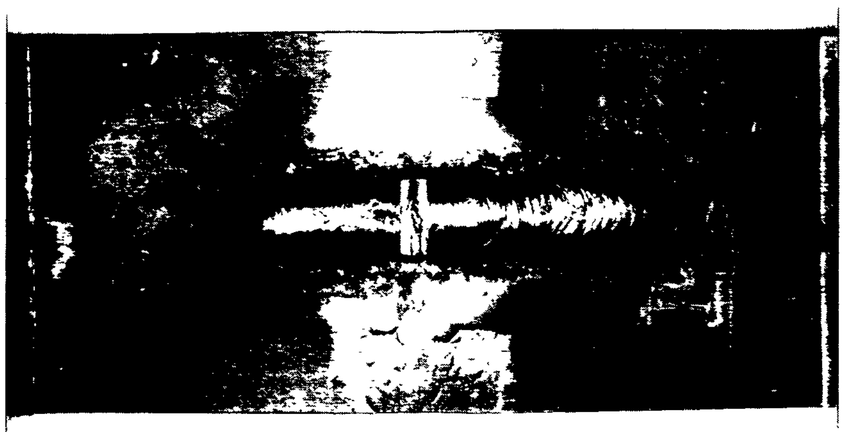


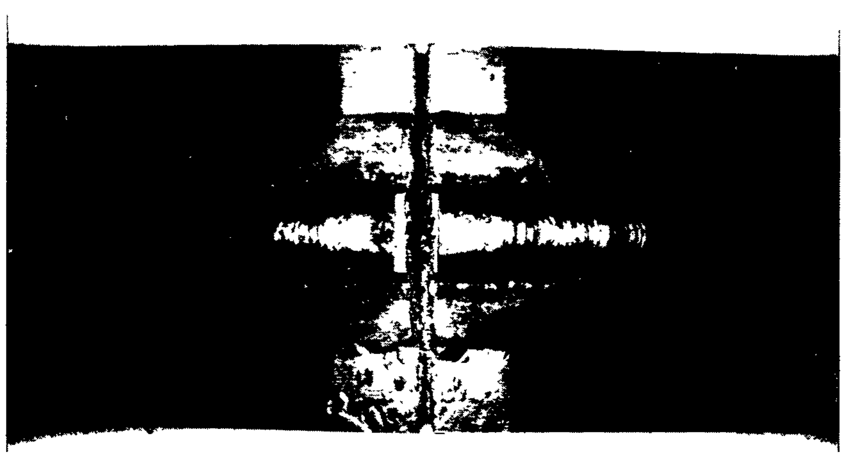
FIGURE 7 - MODIFIED DROP WEIGHT APPARATUS FOR CONDUCTING DYNAMIC TEAR TESTS



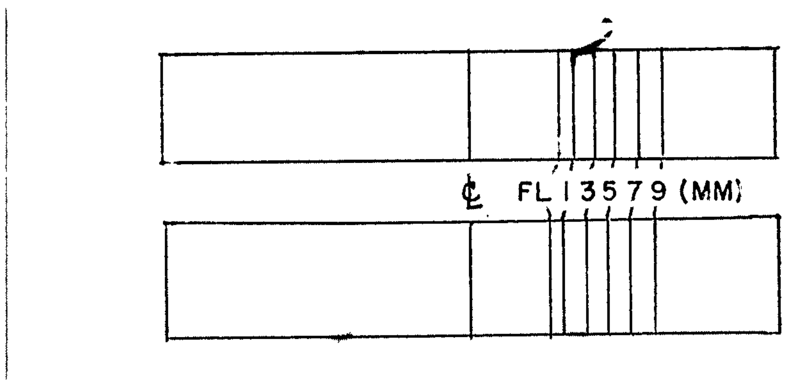
NO BREAK 10 F ABOVE NDT



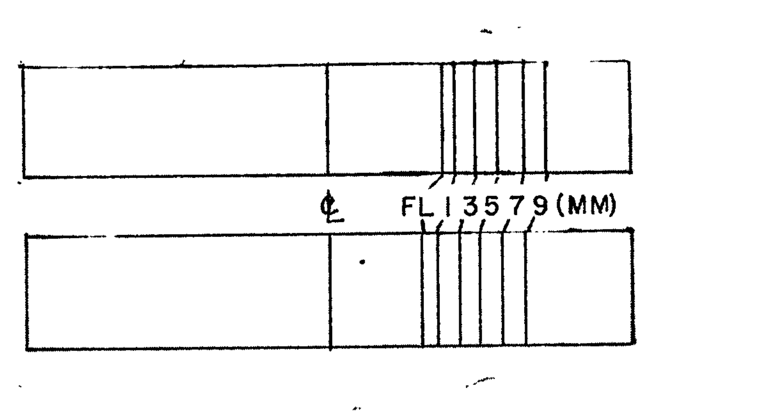
NO BREAK 10 F ABOVE NDT



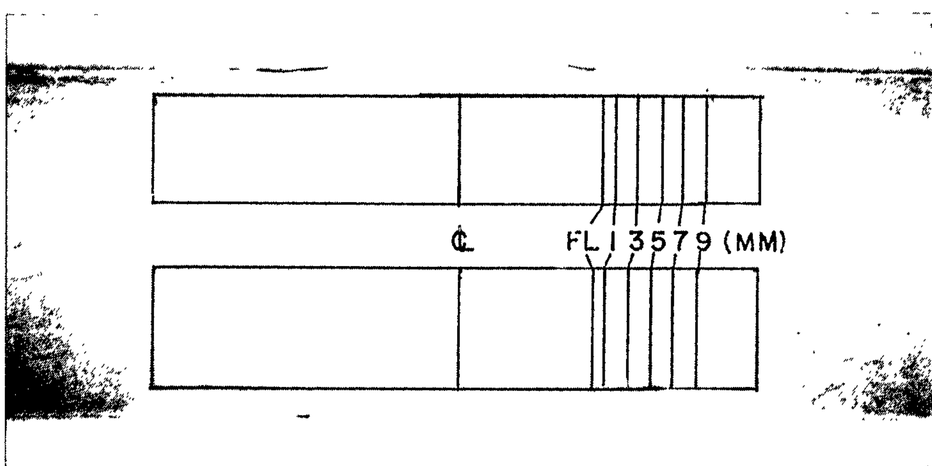
BREAK AT NDT



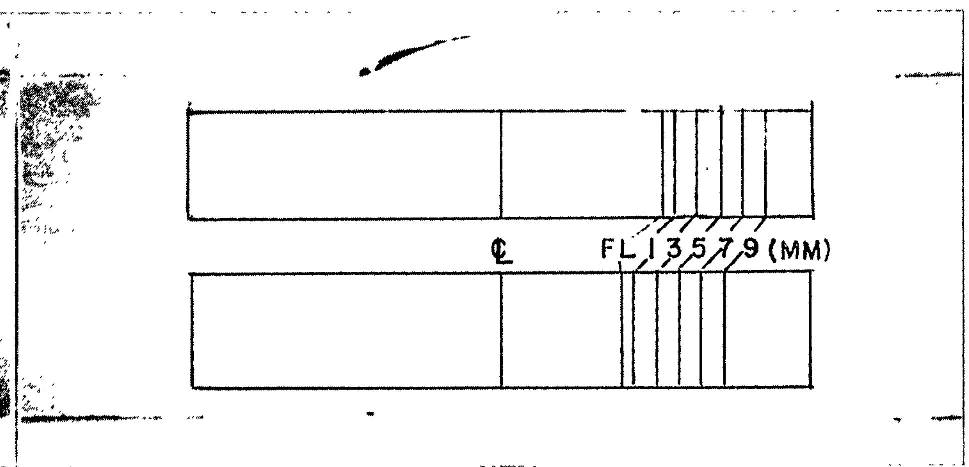
MMA



SAW



EG



ES

FIGURE 9 - CHARPY V-NOTCH TEST - NOTCH LOCATIONS

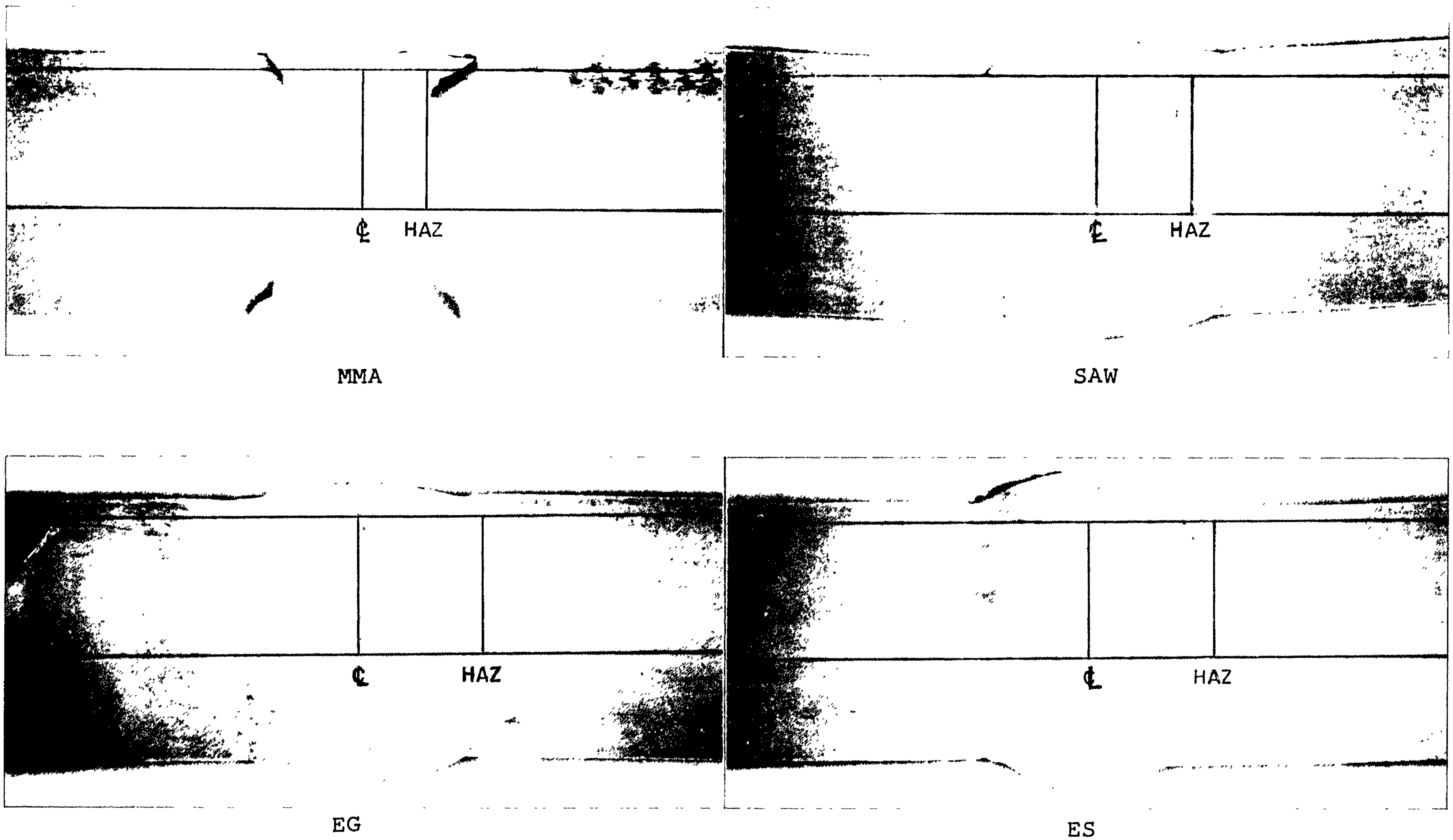


FIGURE 10 - DYNAMIC TEAR TEST - NOTCH LOCATIONS

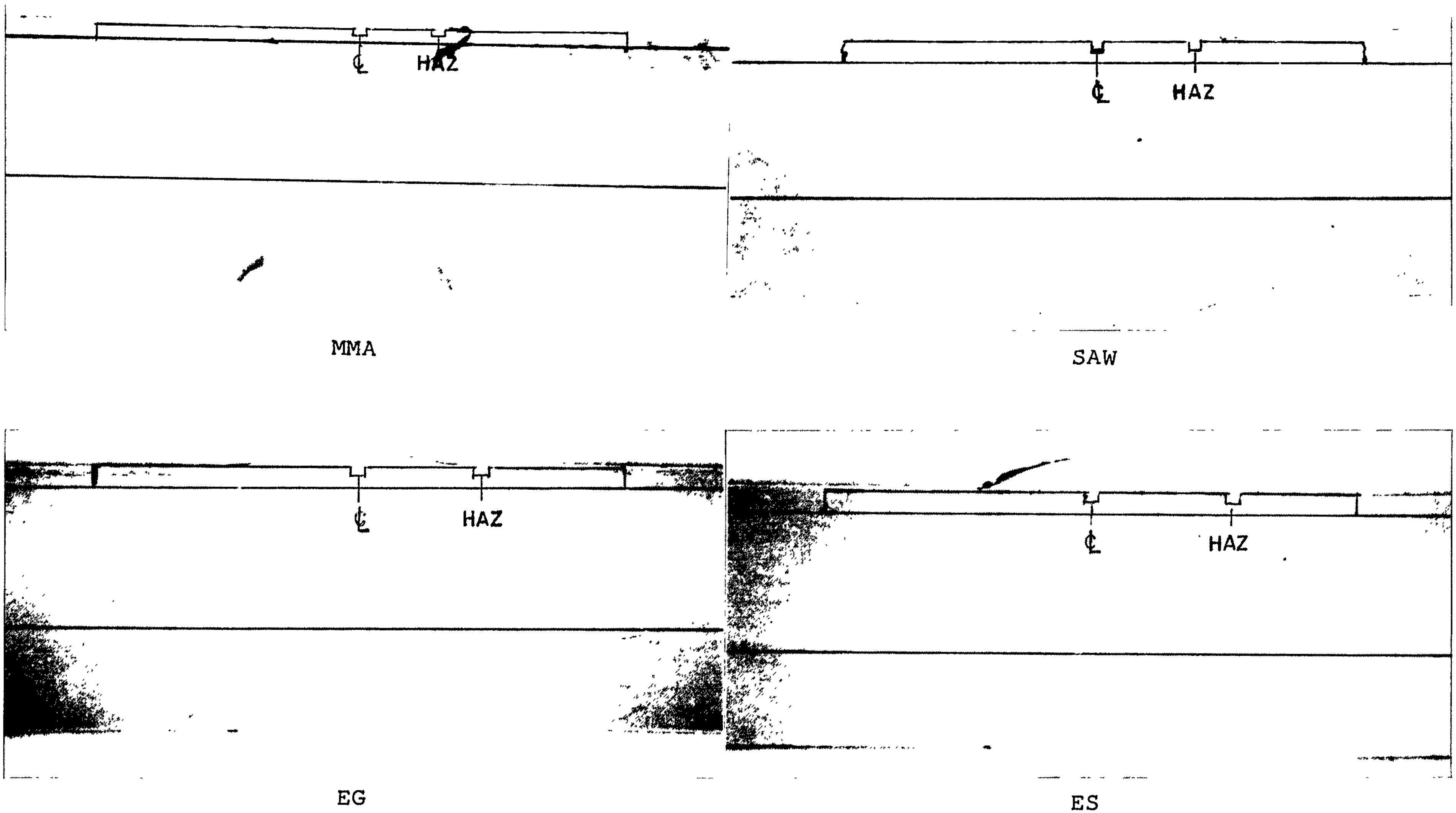


FIGURE 11 - DROP WEIGHT TEST - NOTCH LOCATIONS

AFTER 3 SHOTS

AFTER 4 SHOTS

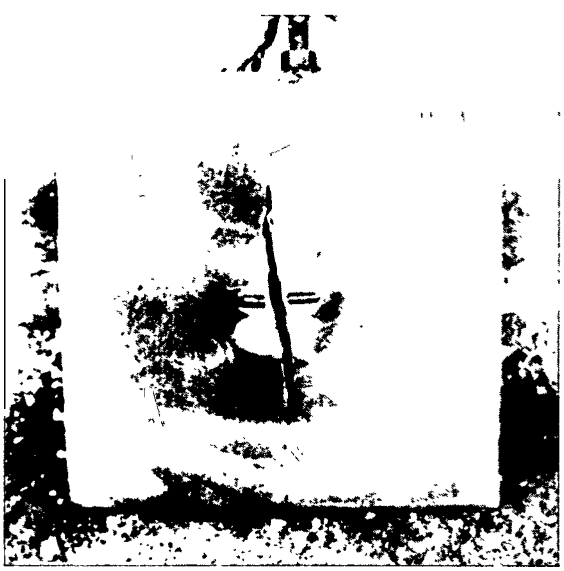
GRADE B - 7 LB. CHARGE AND 17 IN. STANDOFF DISTANCE
(TEST TEMPERATURE 30F)

AFTER 3 SHOTS

GRADE EH36 - 12 LB. CHARGE AND 19 IN. STANDOFF DISTANCE
(TEST TEMPERATURE -20F)

FIGURE 12 - EXPLOSION BULGE TESTS OF BASE MATERIAL TO
ESTABLISH CHARGE AND STAND OFF DISTANCE

AFTER 1 SHOT 80F
(7 LB. CHARGE AND 17 IN. STAND OFF DISTANCE)



AFTER 1 SHOT 120F

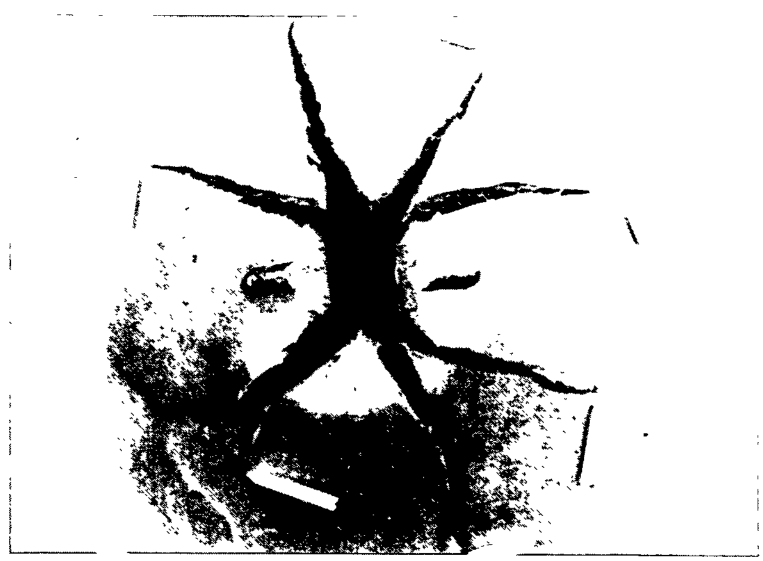
AFTER 2 SHOTS 120F

(7 LB. CHARGE AND 17 IN. STANDOFF DISTANCE)

FIGURE 13 - CRACK STARTER TESTS IN GRADE B MATERIAL TO ESTABLISH TEST TEMPERATURE

AFTER 1 SHOT OF
(12 LB. CHARGE AND 19 IN. STAND OFF DISTANCE)

AFTER 1 SHOT 20F



AFTER 2 SHOTS 20F

(12 LB. CHARGE 19 IN. STAND OFF DISTANCE)

FIGURE 14 - CRACK STARTER TESTS IN GRADE CS MATERIAL TO ESTABLISH TEST TEMPERATURE

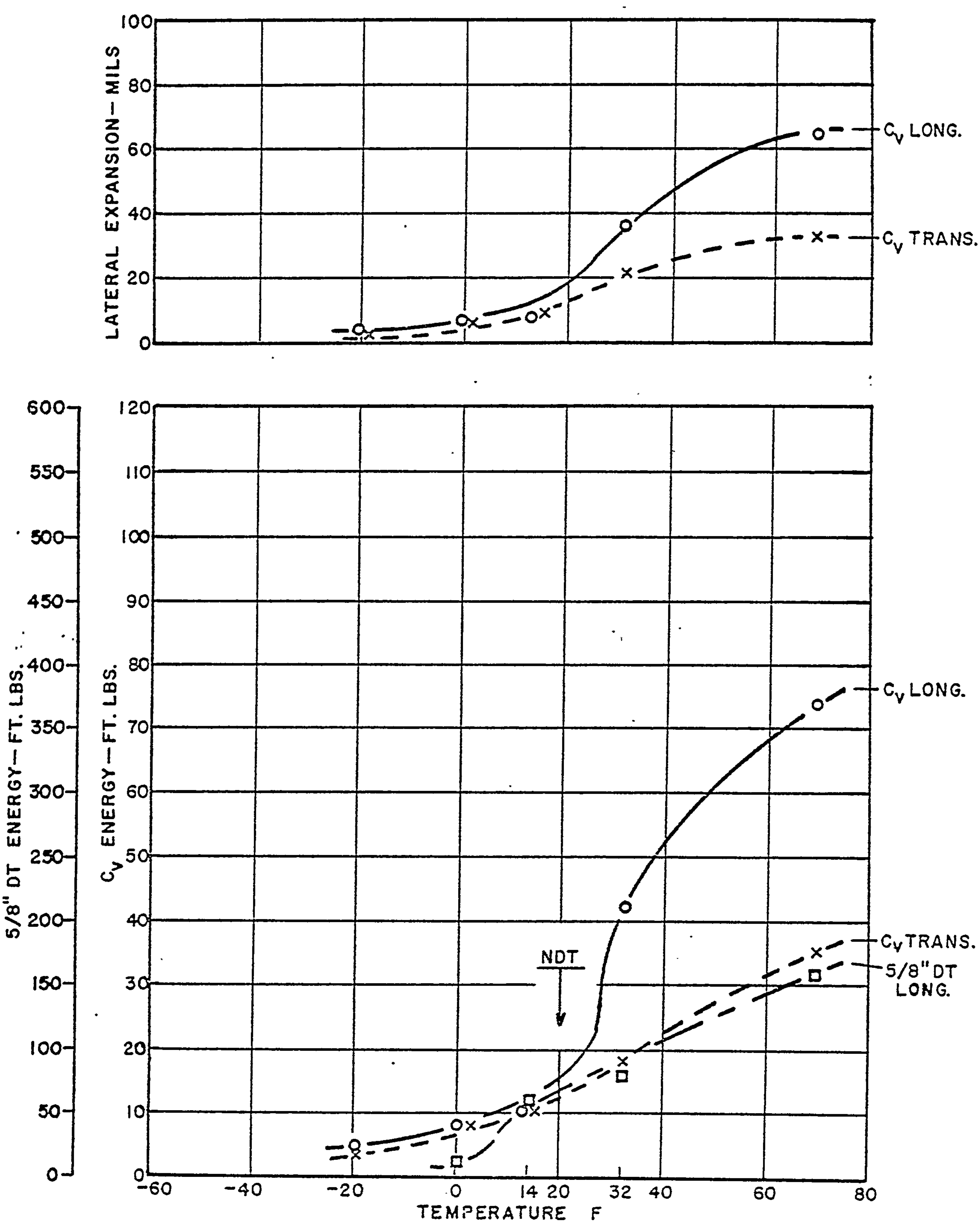


FIGURE 15 - SMALL SCALE TOUGHNESS DATA OF GRADE B MATERIAL (1")

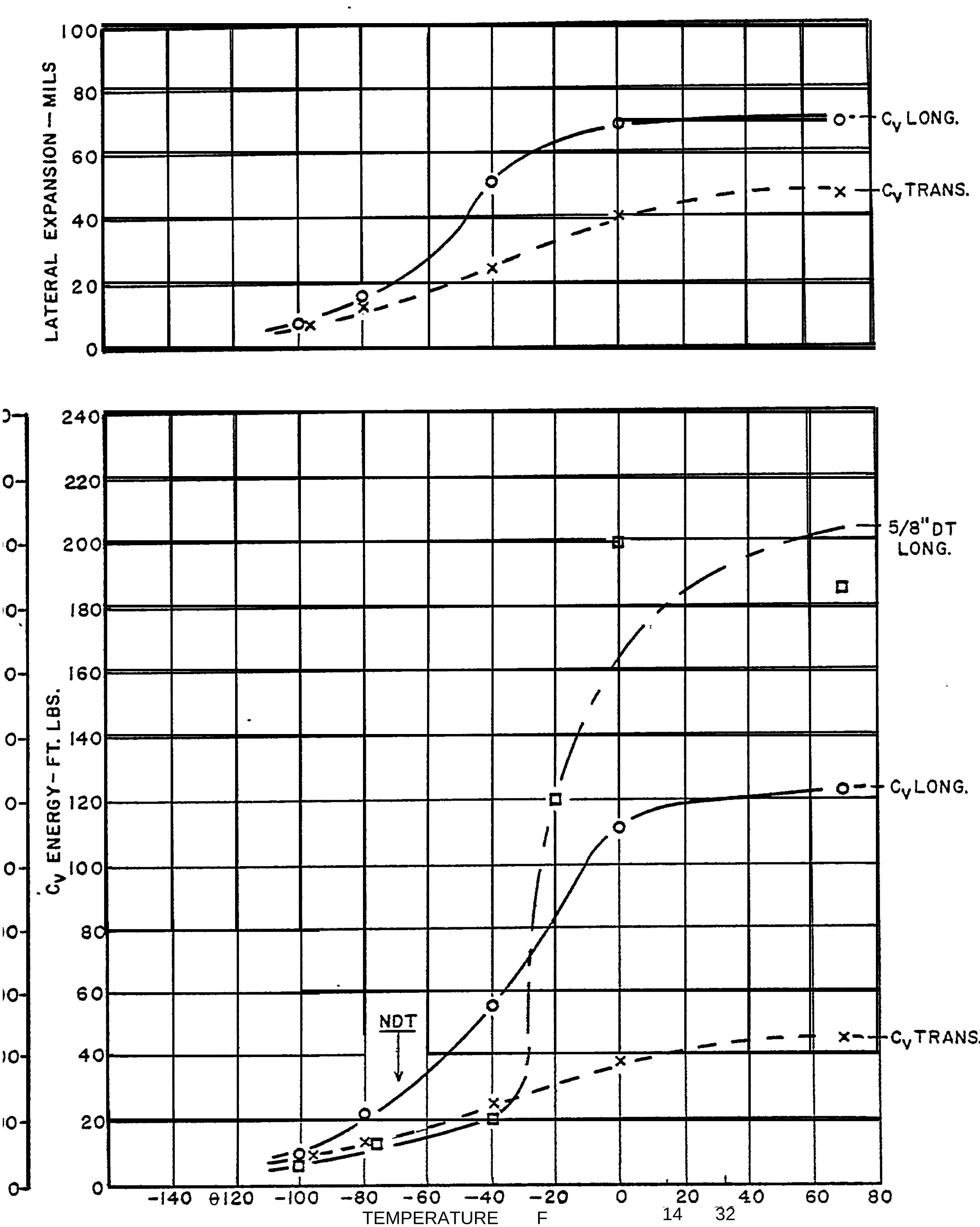


FIGURE 16 - SMALL SCALE TOUGHNESS DATA OF GRADE Cs MATERIAL 1 1/4")

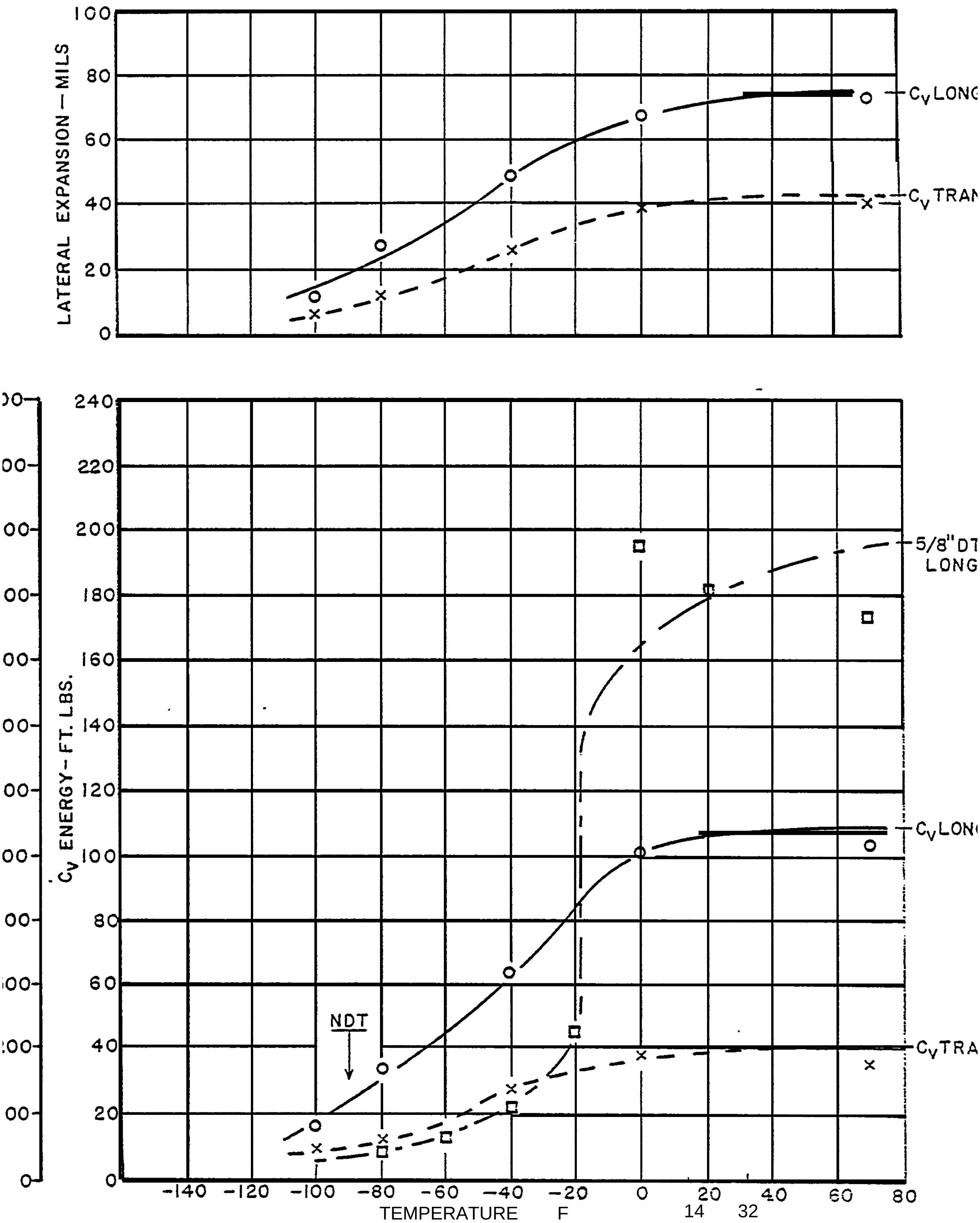


FIGURE 17 - SMALL SCALE TOUGHNESS DATA OF GRADE EH36 MATERIAL (1 1/4")

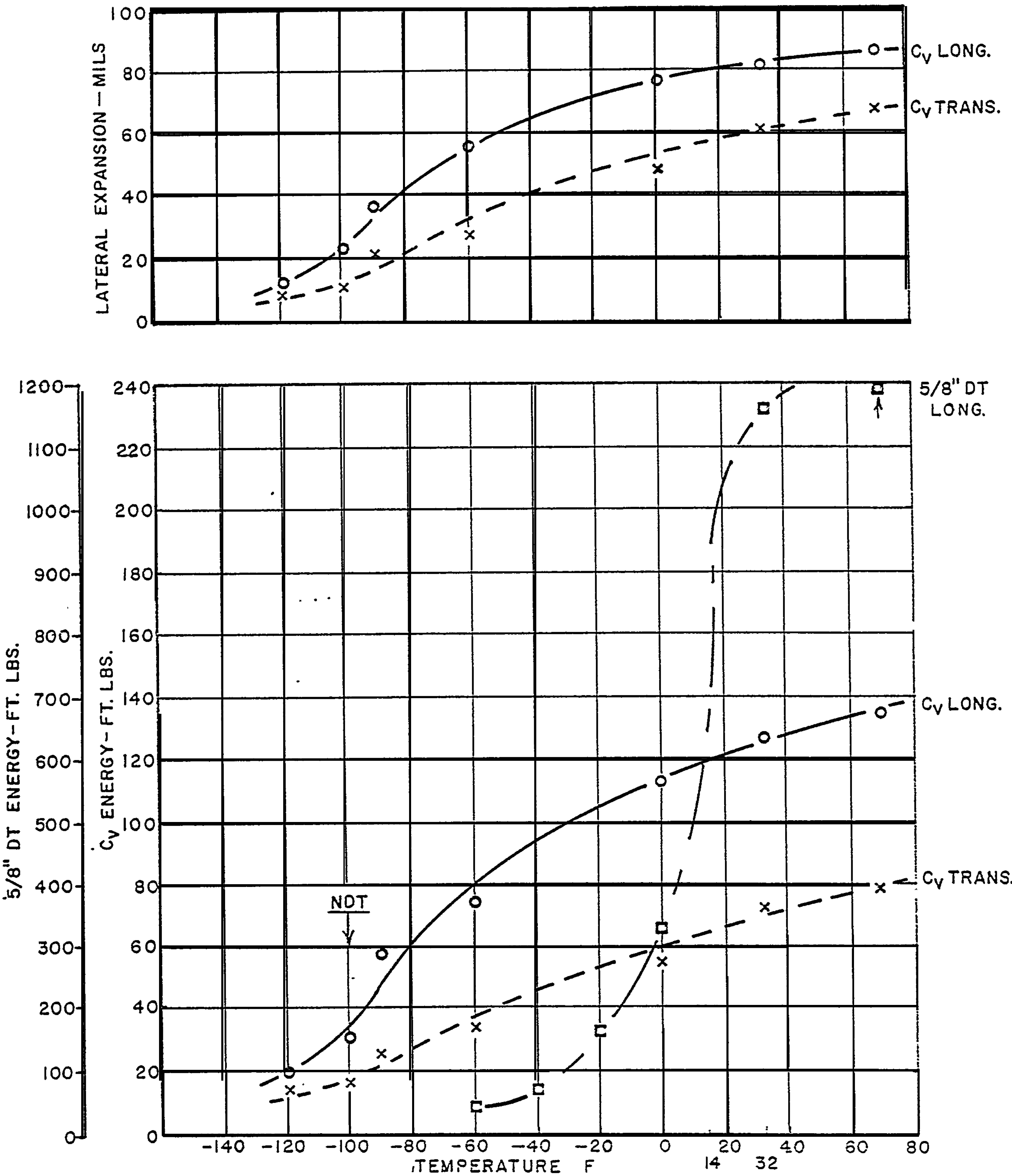
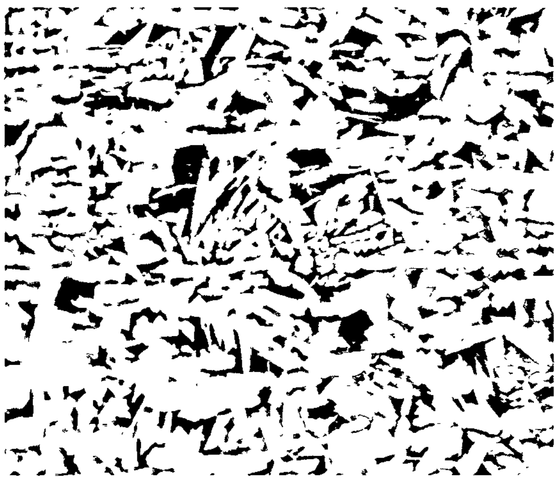
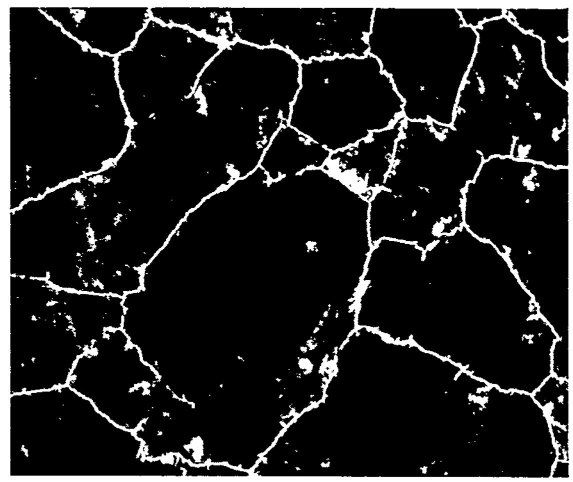


FIGURE 18 - SMALL SCALE TOUGHNESS DATA OF ASTM A203 GRADE A MATERIAL (1 1/4")

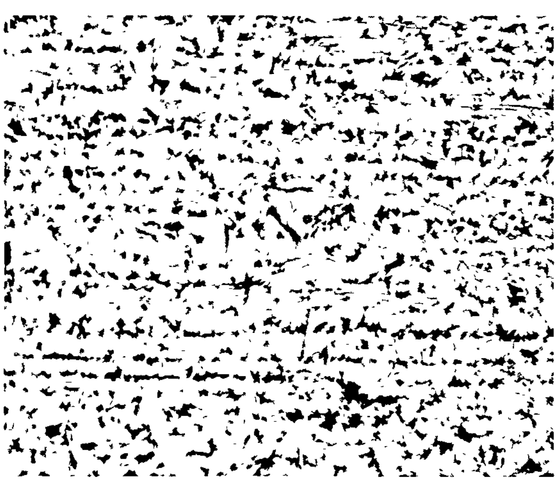


MICROSTRUCTURE

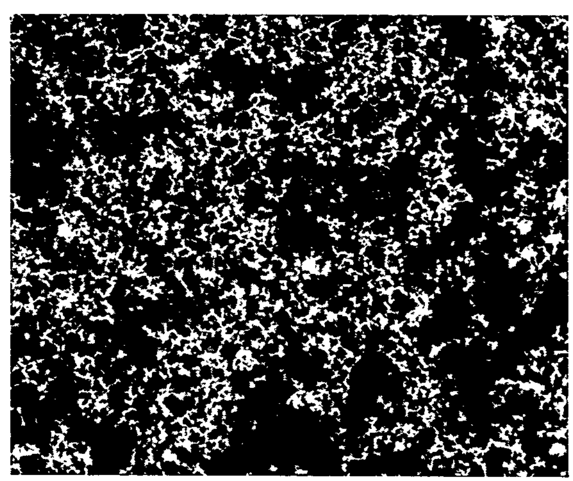


McQUAID EHN GRAIN SIZE 1-3

FIGURE 19 - PHOTOMICROGRAPHS OF GRADE B MATERIAL (2% NITAL ETCH - 100X)

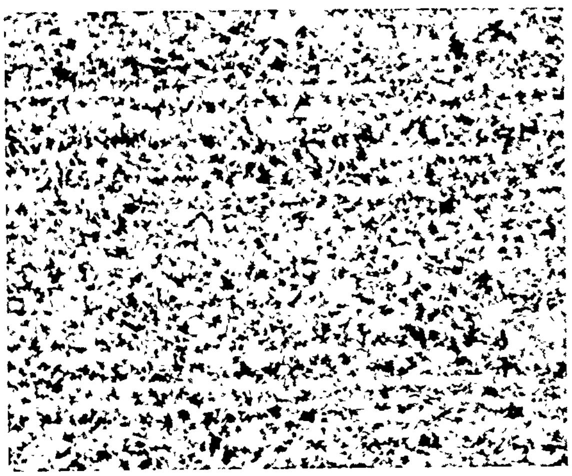


MICROSTRUCTURE

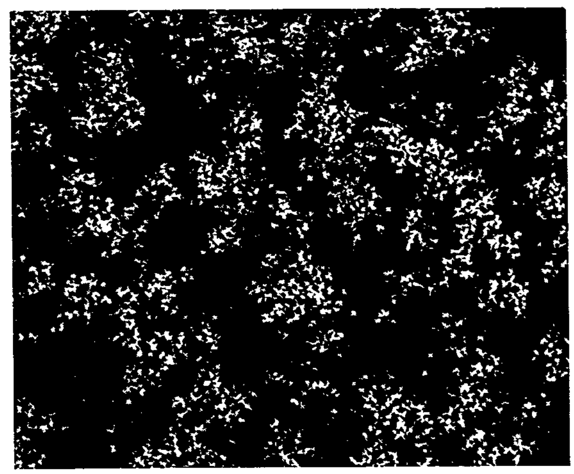


McQUAID EHN GRAIN SIZE 7-8

FIGURE 20 - PHOTOMICROGRAPHS OF GRADE CS MATERIAL (2% NITAL ETCH - 100 X)

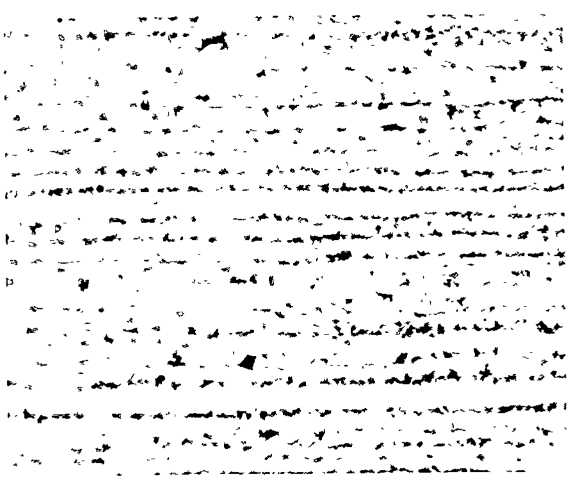


MICROSTRUCTURE

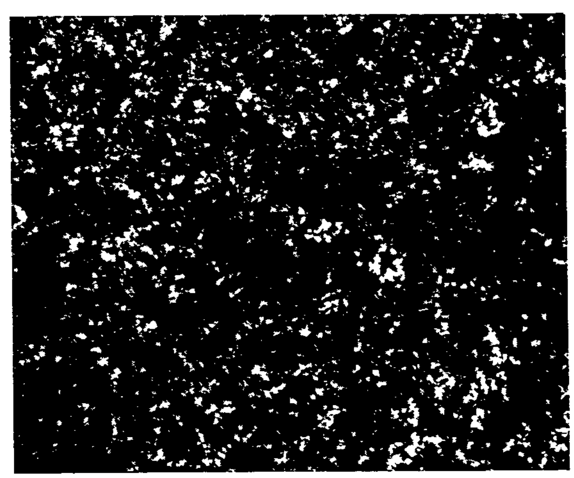


McQUAID EHN GRAIN SIZE 7-8

FIGURE 21 - PHOTOMICROGRAPHS OF GRADE EH36 (2% NITAL ETCH - 100X)



MICROSTRUCTURE



McQUAID EHN GRAIN SIZE 7-8

FIGURE 22 - PHOTOMICROGRAPHS OF ASTM A203 GRADE A MATERIAL (2% NITAL ETCH - 100 X

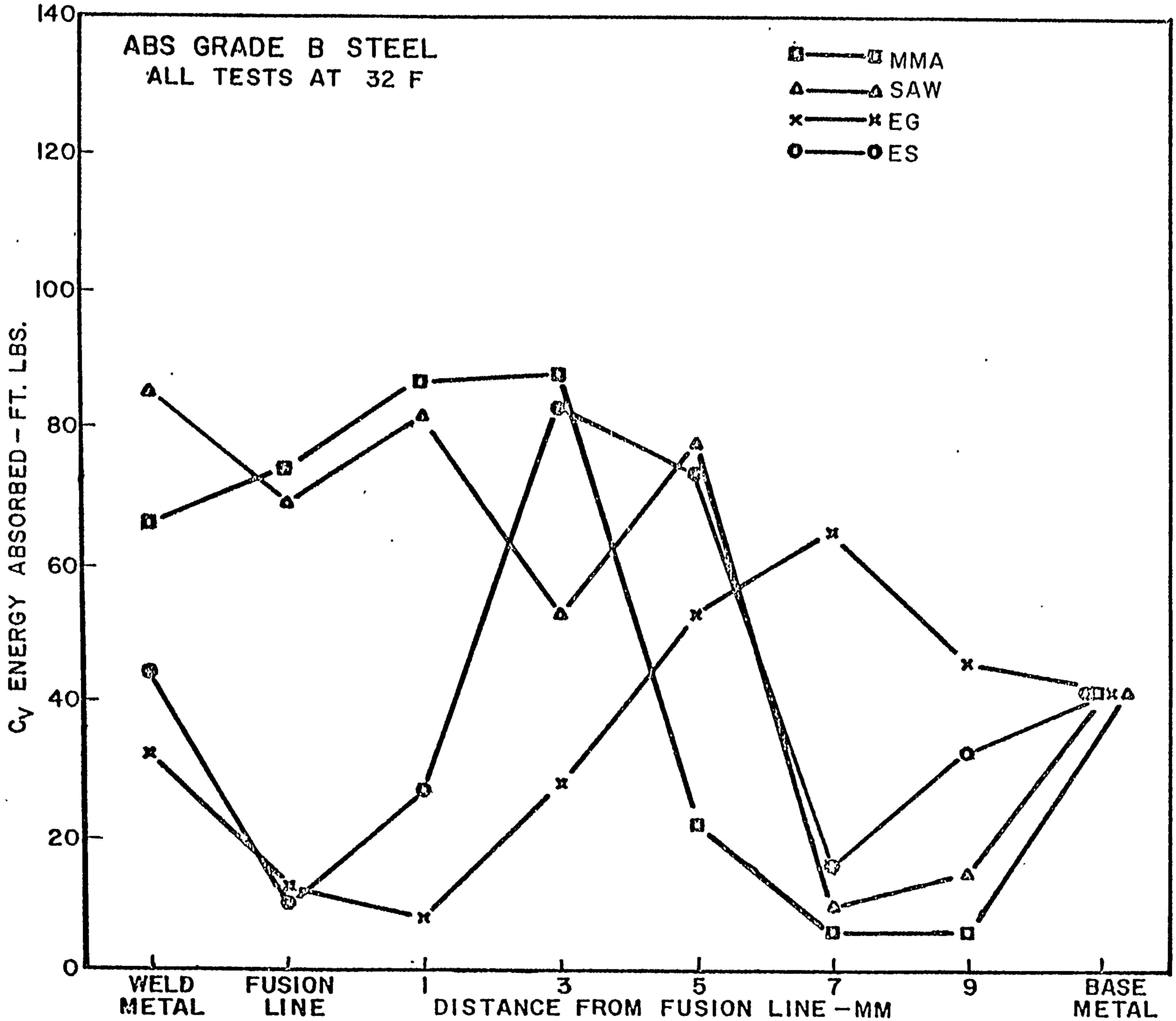


FIGURE 23 - WELD METAL AND HAZ CHARPY V-NOTCH TEST RESULTS GRADE B

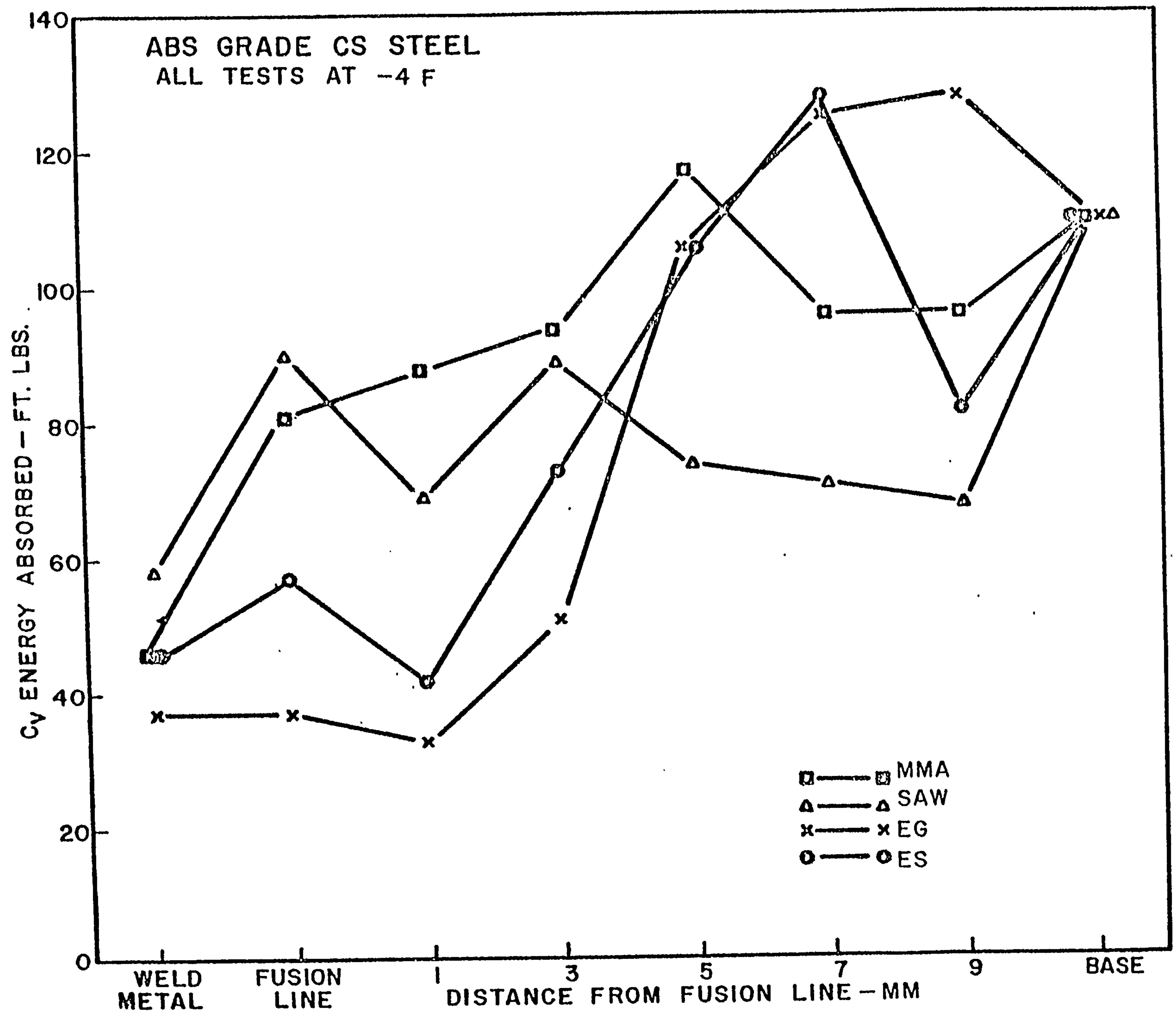


FIGURE 24 - WELD METAL AND HAZ CHARPY V-NOTCH TEST RESULTS GRADE CS

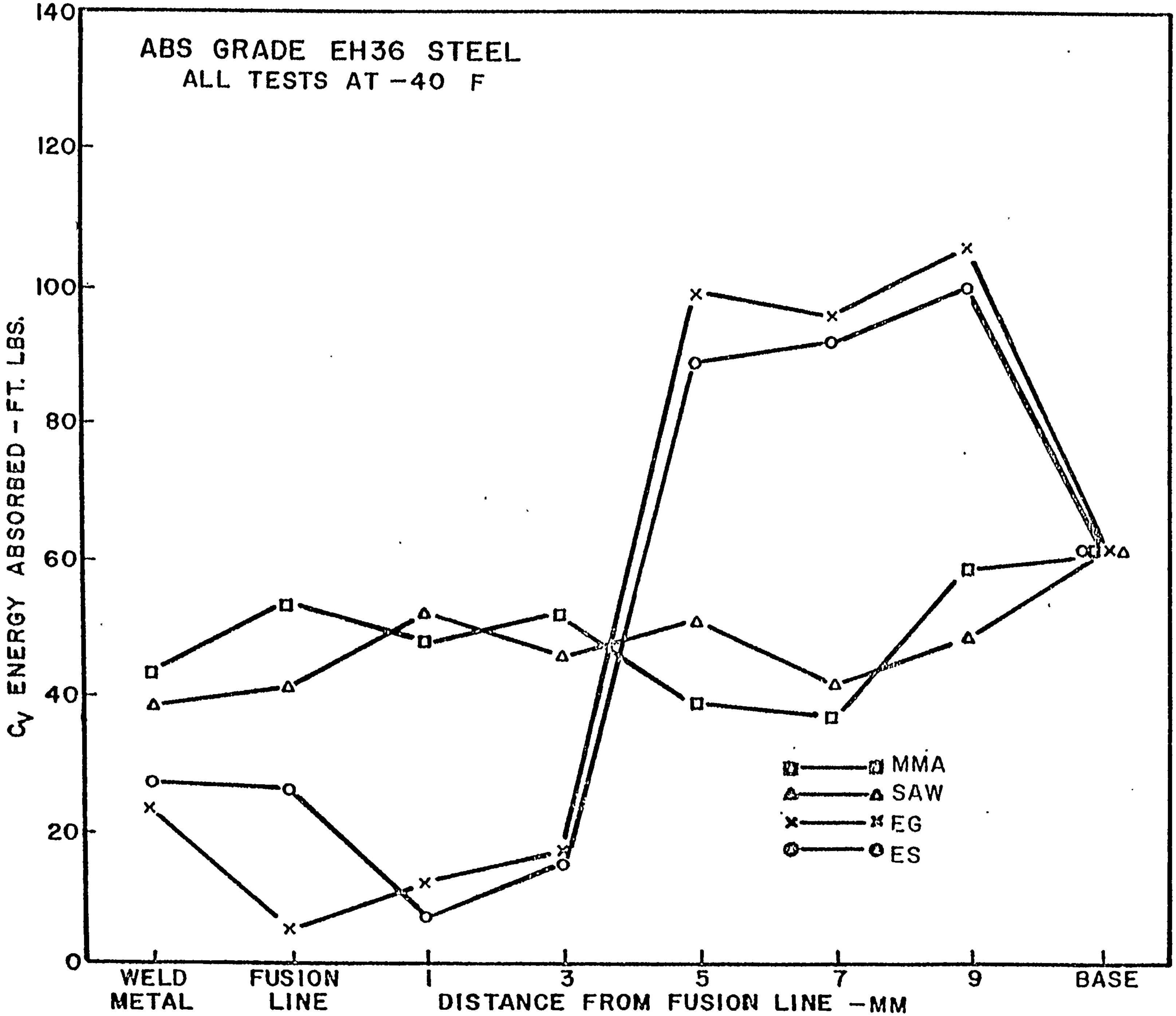


FIGURE 25 - WELD METAL AND HAZ CHARPY V-NOTCH TEST RESULTS GRADE EH36

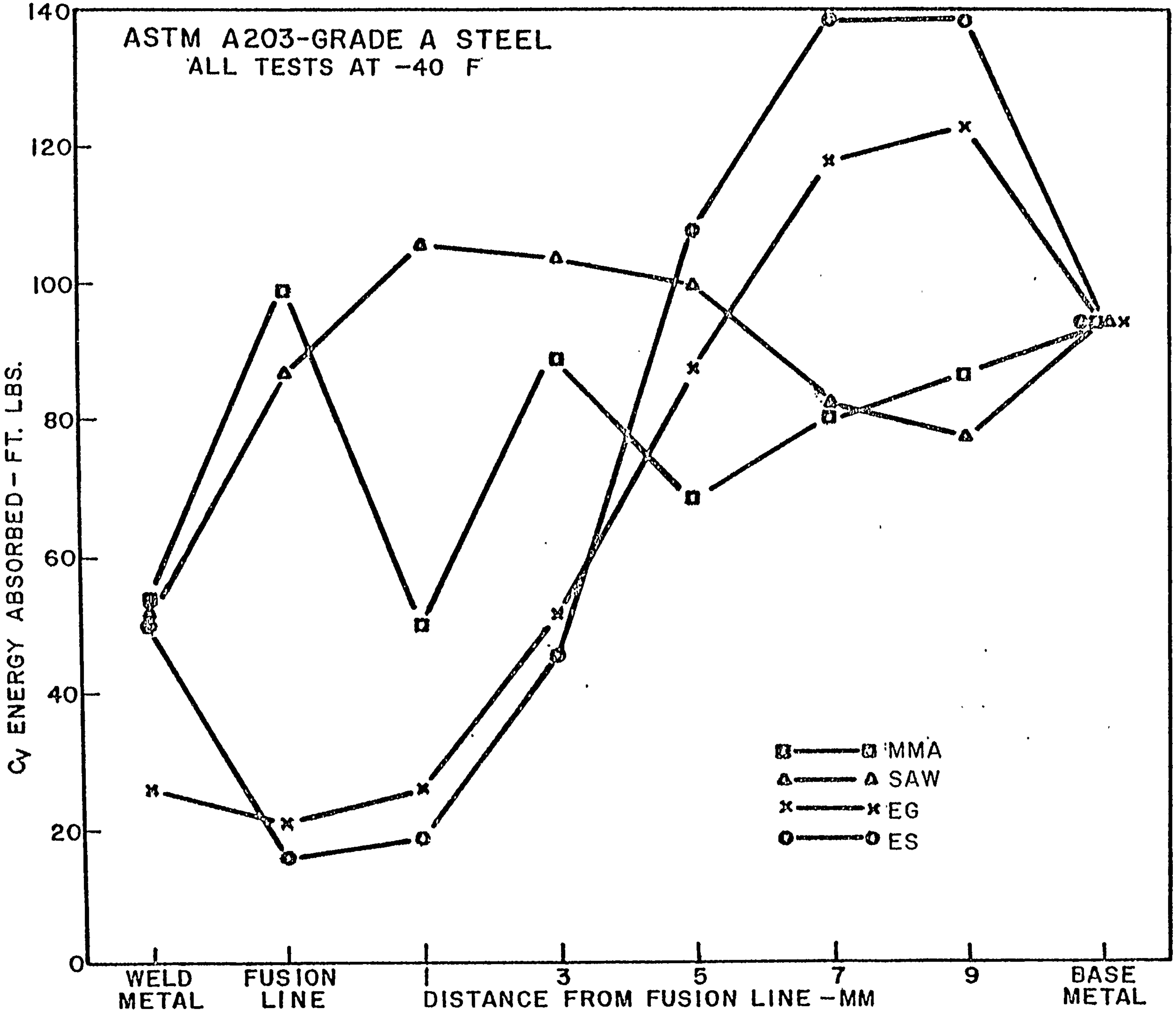


FIGURE 26 - WELD METAL AND HAZ CHARPY V-NOTCH TEST RESULTS ASTM A203 GRADE A MATERIAL

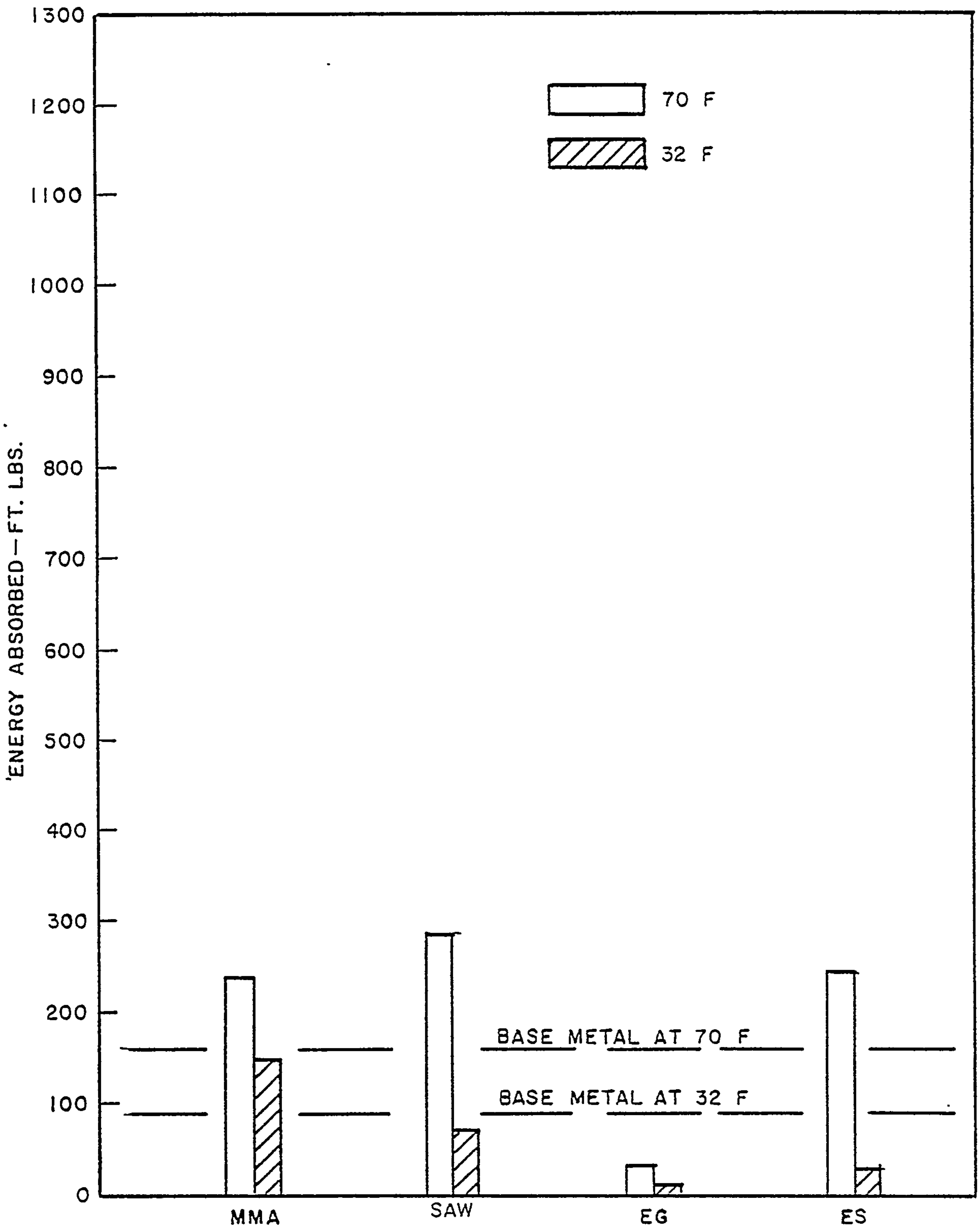


FIGURE 27 - DYNAMIC TEAR HAZ TEST RESULTS GRADE B MATERIAL

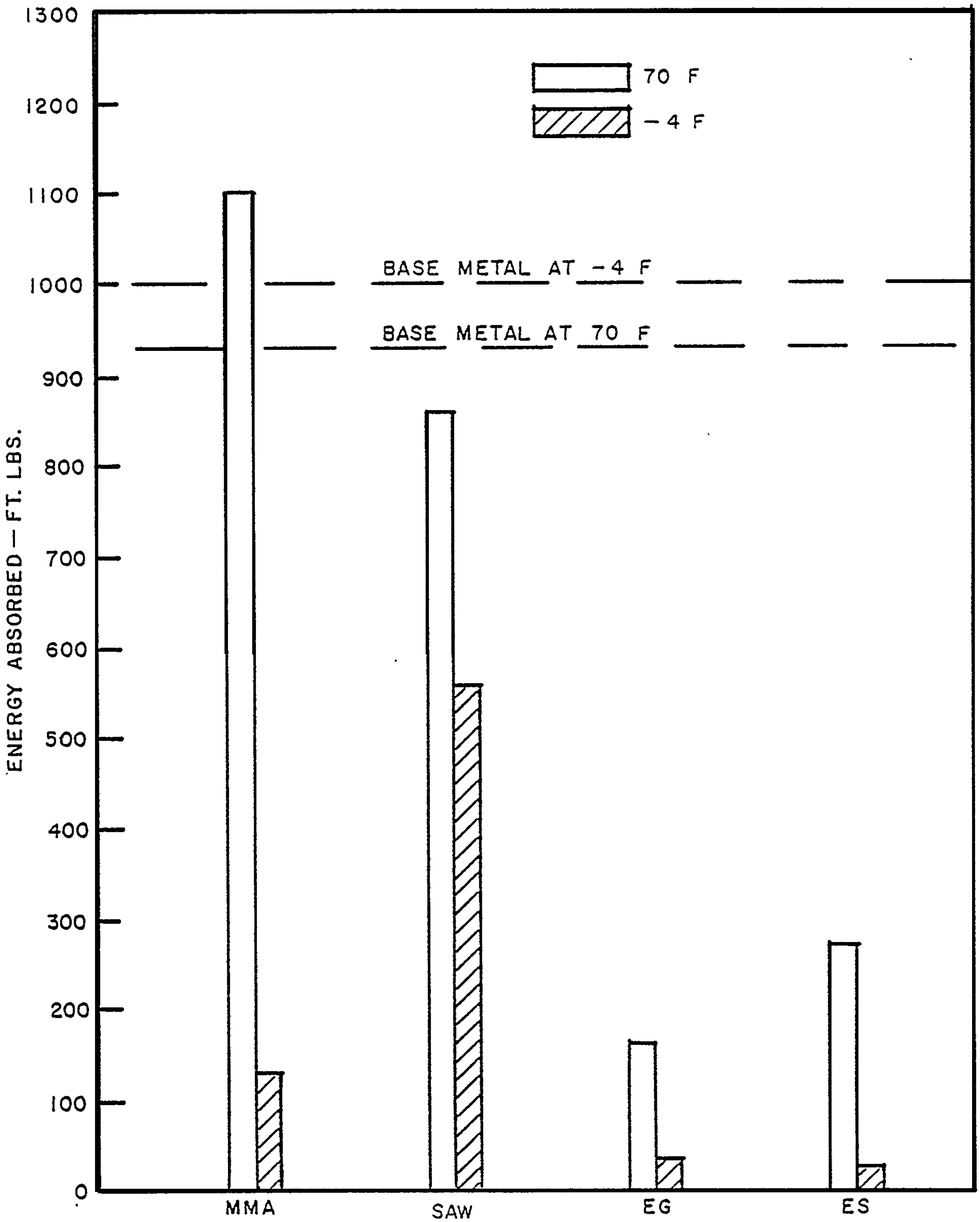


FIGURE 28 - DYNAMIC TEAR HAZ TEST RESULTS GRADE CS MATERIAL

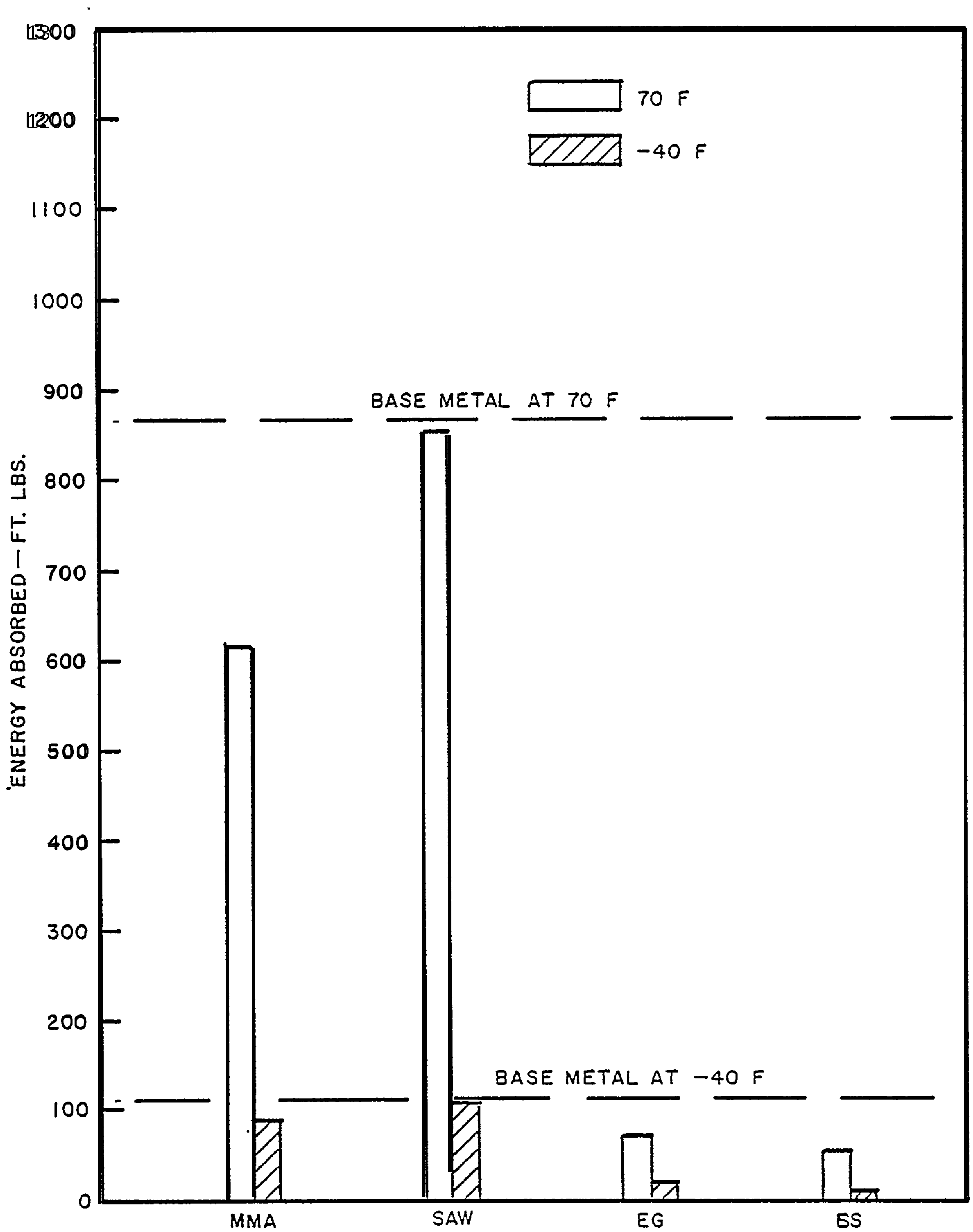


FIGURE 29 - DYNAMIC TEAR HAZ TEST RESULTS GRADE EH36 MATERIAL

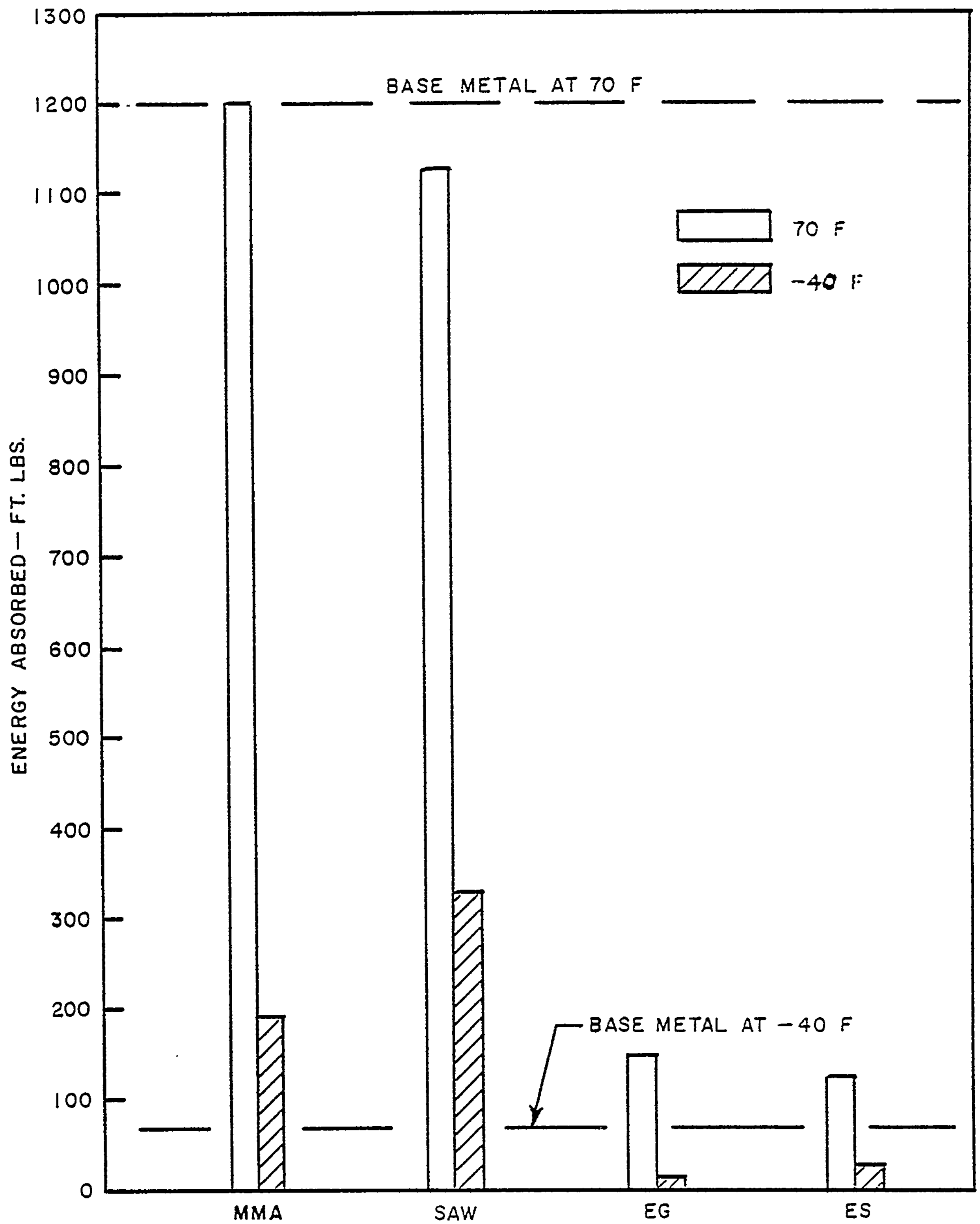
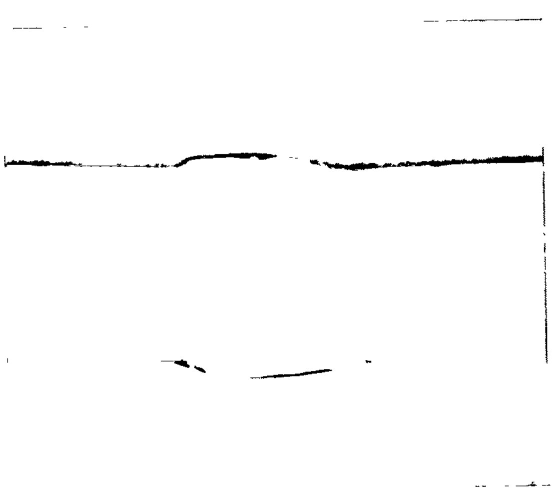
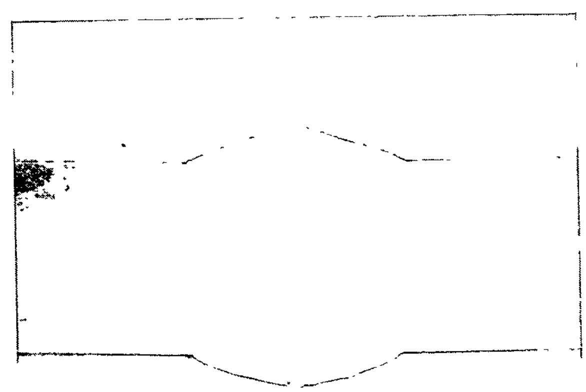


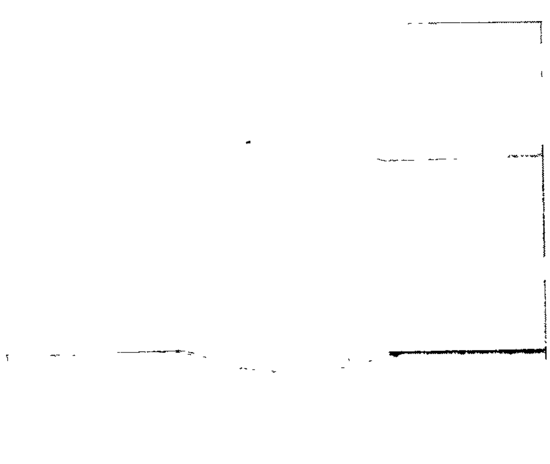
FIGURE 30 - DYNAMIC TEAR HAZ TEST RESULTS ASTM A203 GRADE A MATERIAL



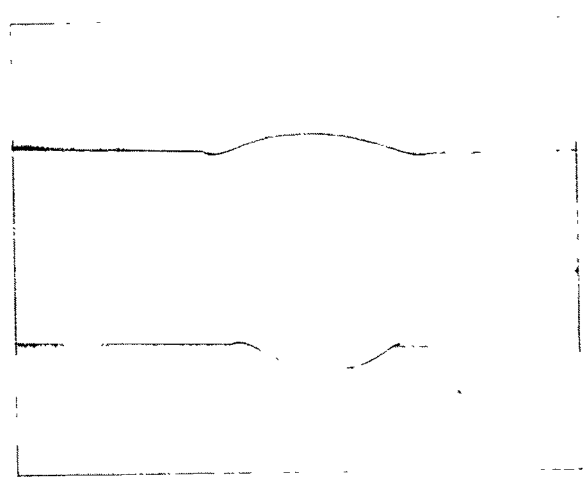
MA



SAW



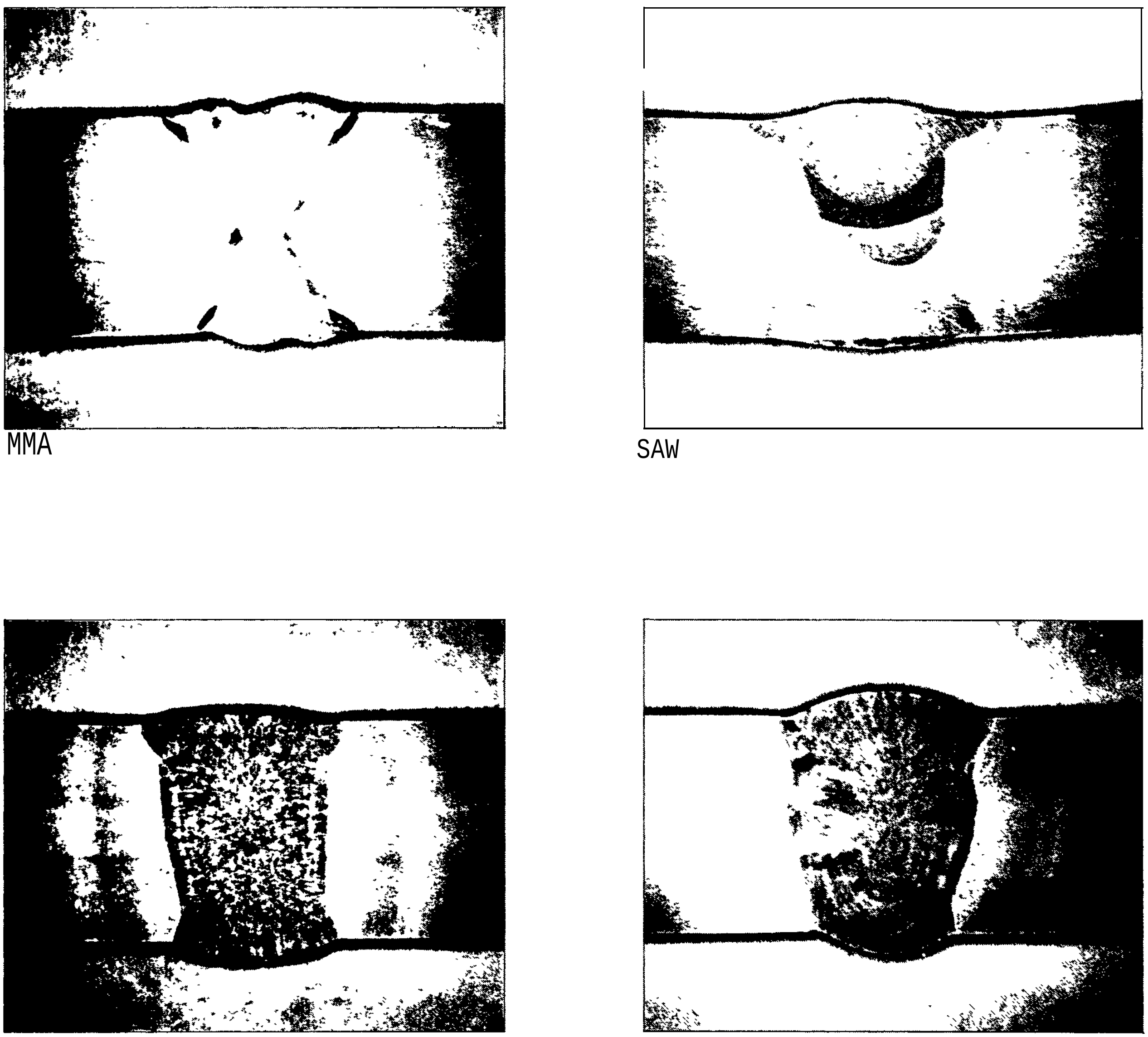
EG



ES

(10% NITAL ETCH - ACTUAL SIZE)

FIGURE 31 - MACROSECTIONS OF WELDS IN GRADE B MATERIAL

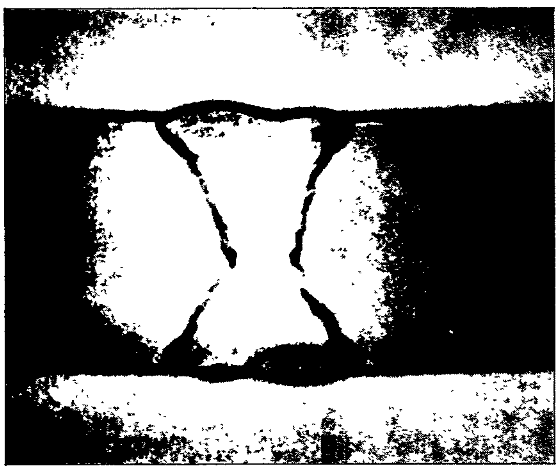


MMA SAW

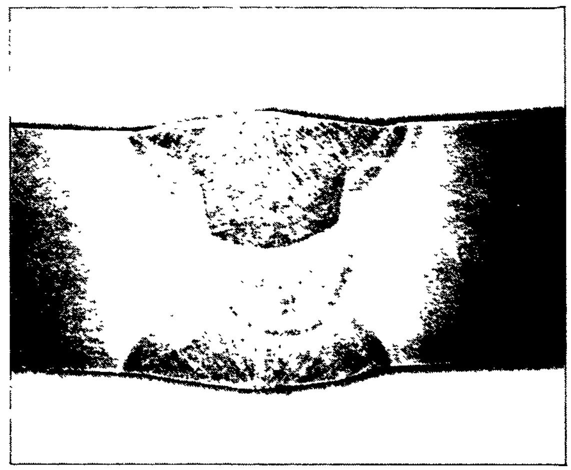
EG ES

(10% NITAL ETCH - ACTUAL SIZE)

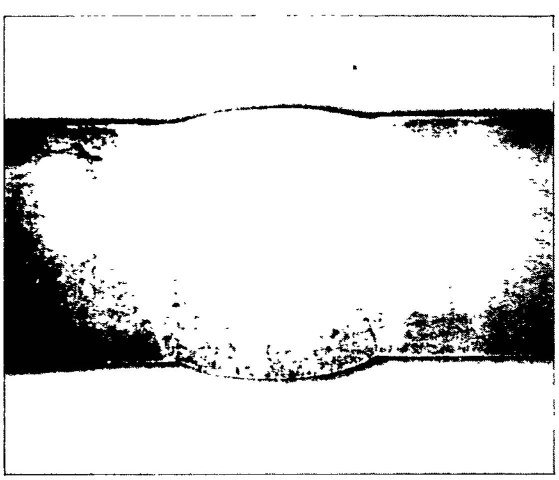
FIGURE 32 - MACROSECTIONS OF WELDS IN GRADE CS MATERIAL



MMA



SAW

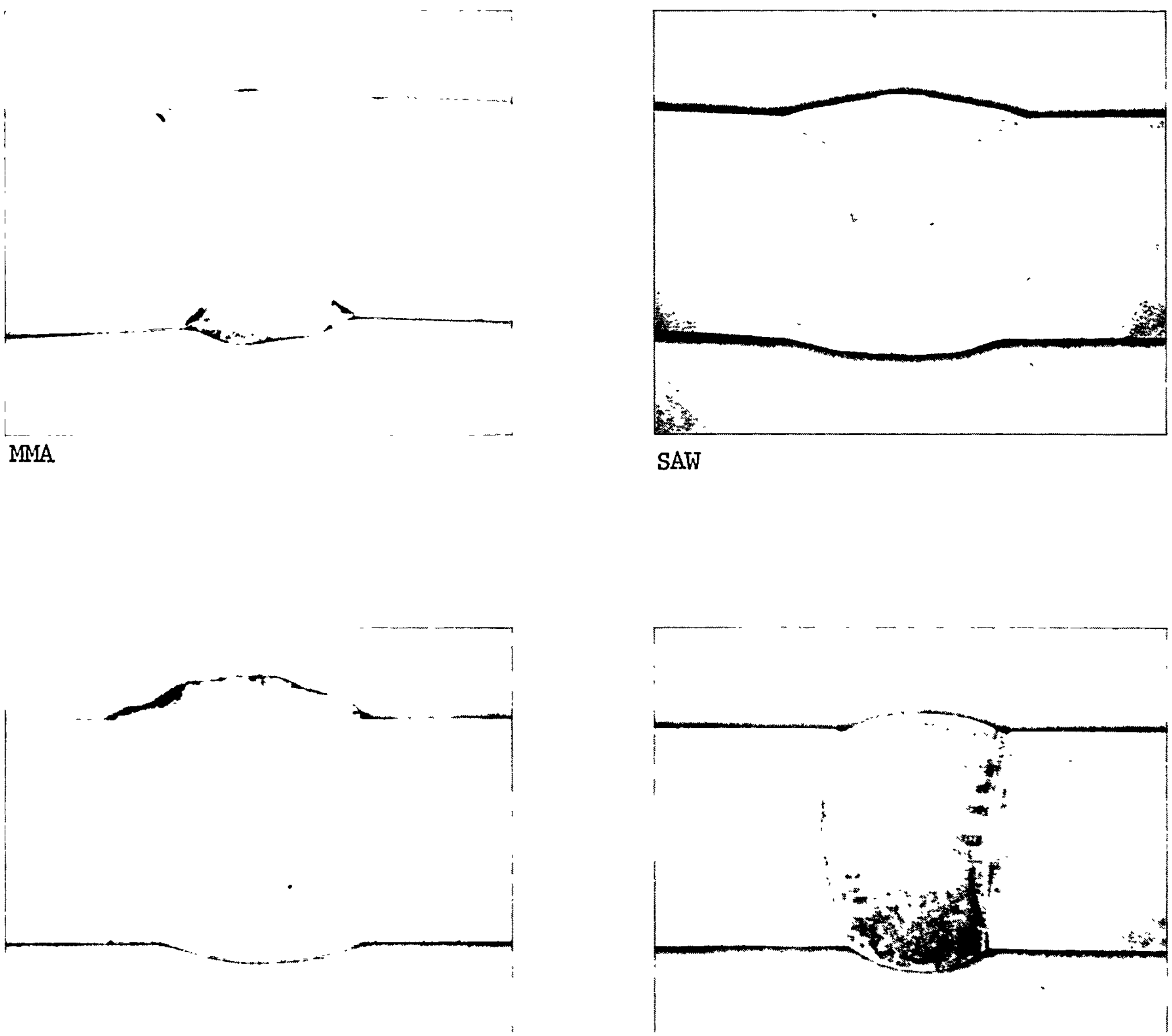


EG

ES

(10% NITAL ETCH - ACTUAL SIZE)

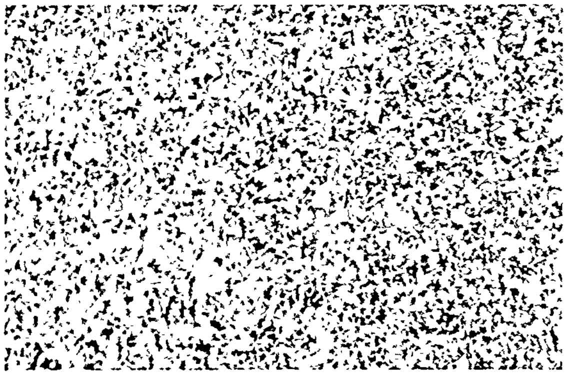
FIGURE 33 - MACROSECTIONS OF WELDS IN GRADE EH36 MATERIAL



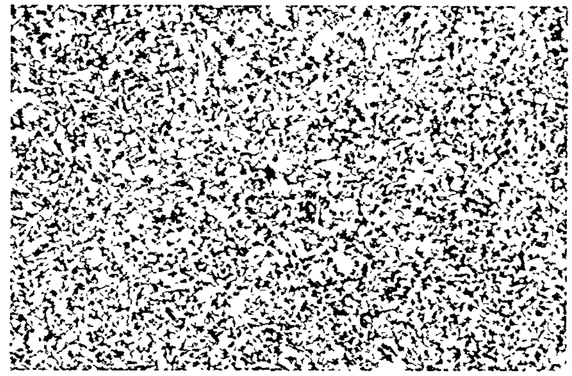
ES

(10% NITAL ETCH - ACTUAL SIZE)

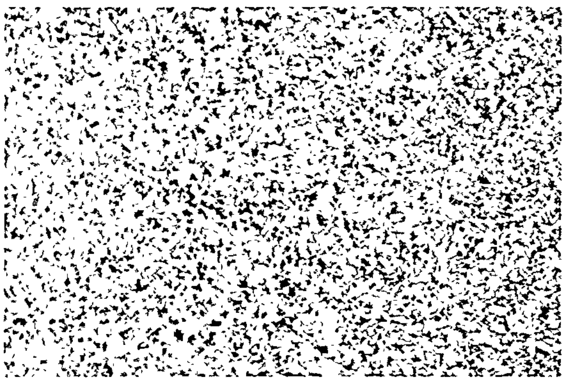
MACROSECTIONS OF WELDS IN ASTM A203 GRADE A MATERIAL



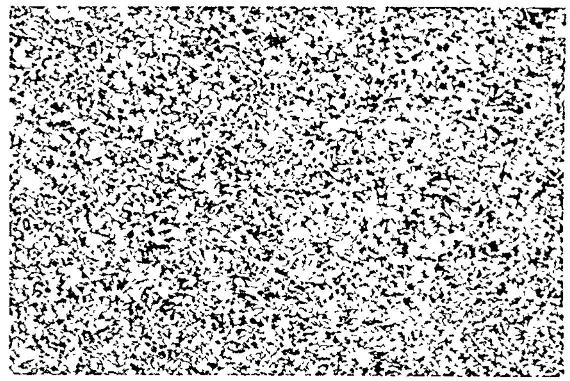
WELD METAL FUSION LINE



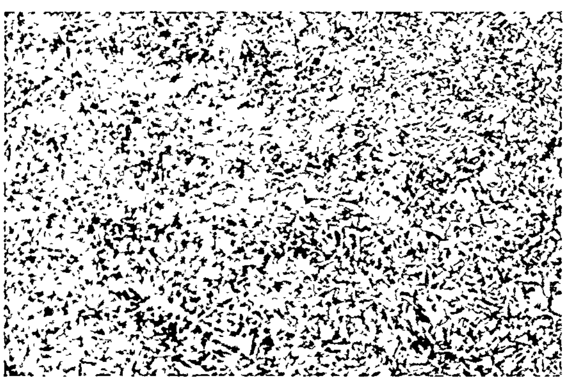
HAZ - 1 MM



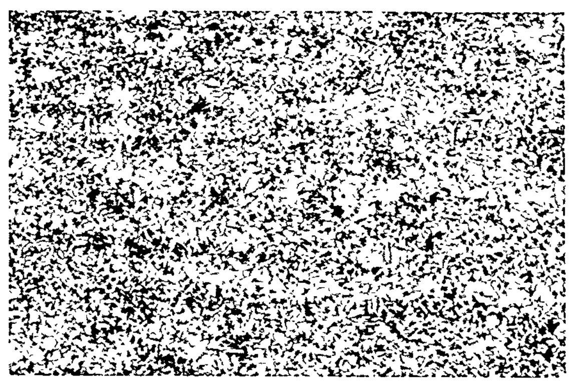
HAZ - 2 MM



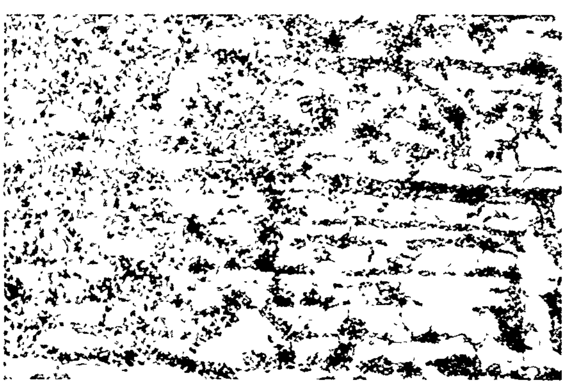
HAZ - 3 MM



HAZ - 4 MM



HAZ - 5 MM

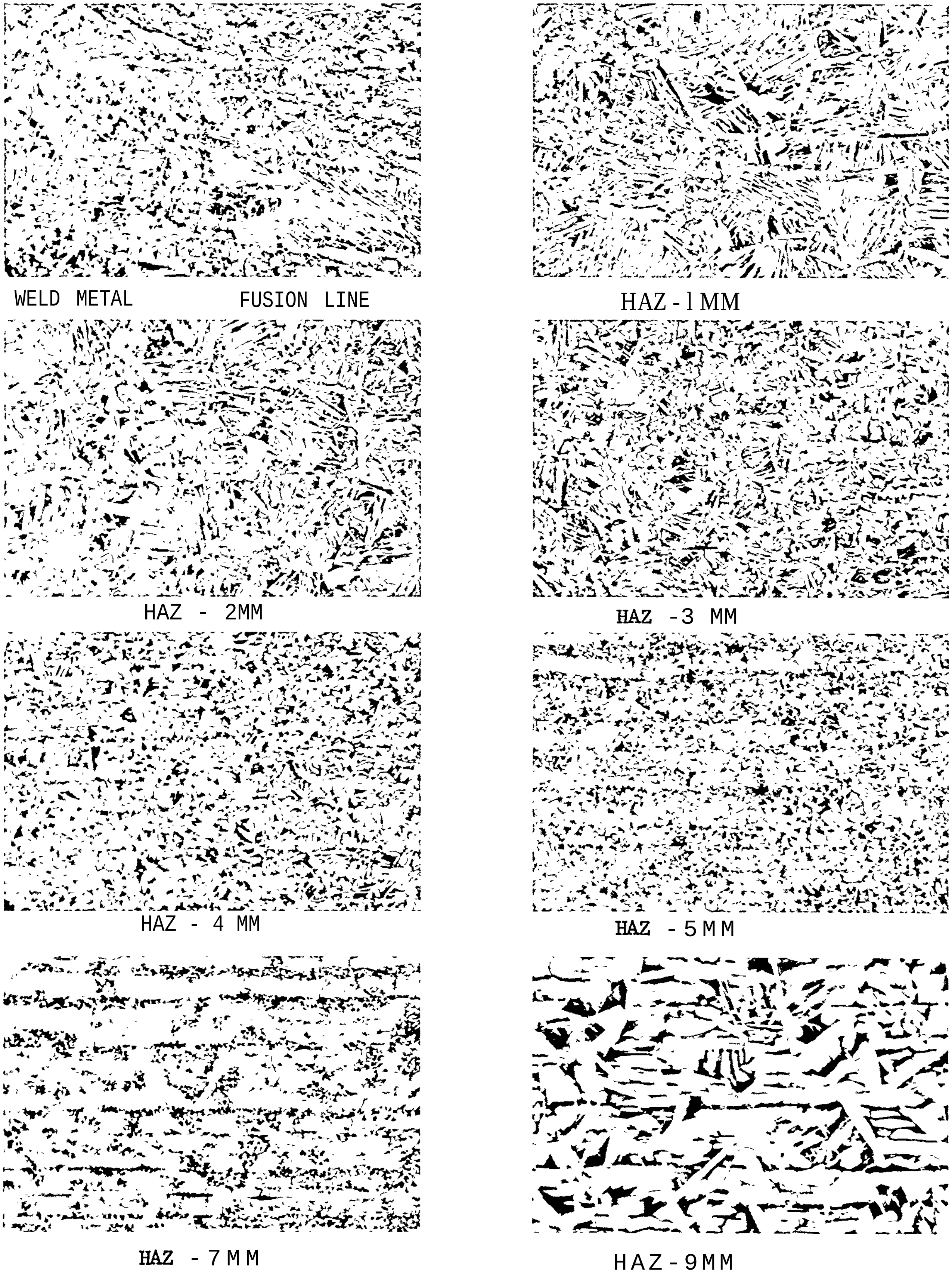


HAZ - 7 MM

HAZ - 9 MM

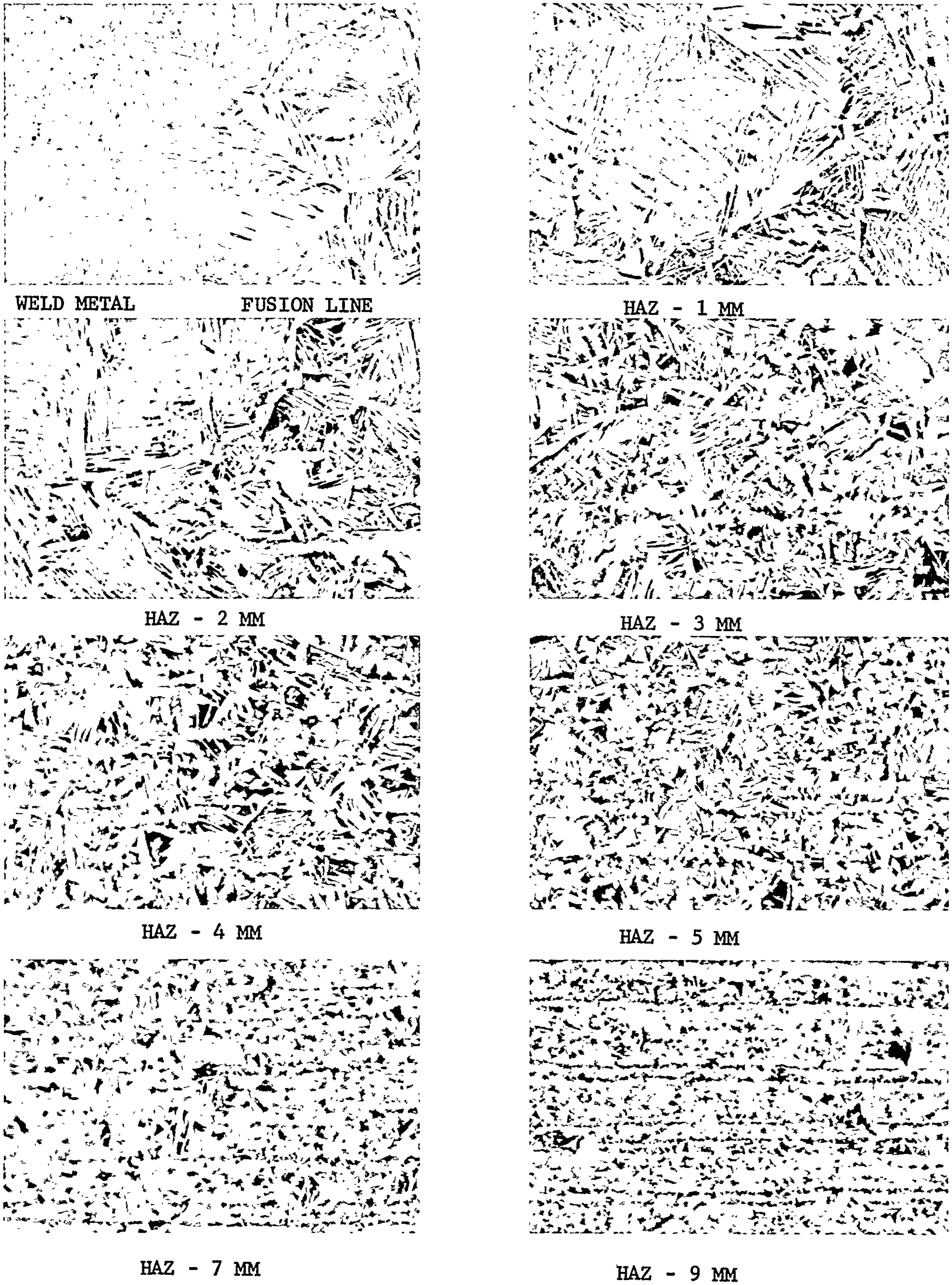
(2% NITAL ETCH - 100 X)

FIGURE 35 - PHOTOMICROGRAPHS OF MMA WELDMENT IN GRADE B MATERIAL



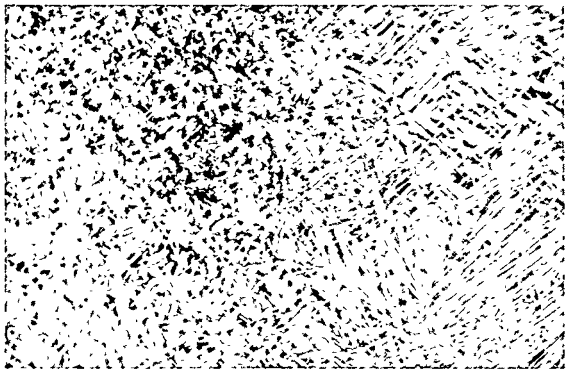
(2% NITAL ETCH - 100 X)

FIGURE 36 - PHOTOMICROGRAPHS OF SAW WELDMENT IN GRADE B MATERIAL

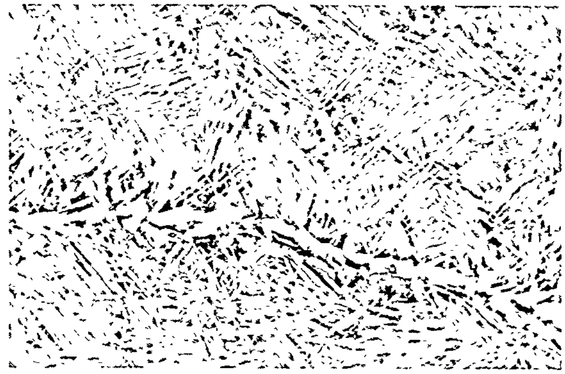


(2% NITAL ETCH - 100 X)

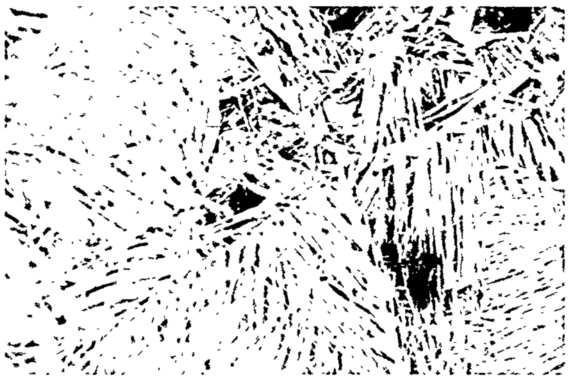
FIGURE 37 - PHOTOMICROGRAPHS OF EG WELDMENT IN GRADE B MATERIAL



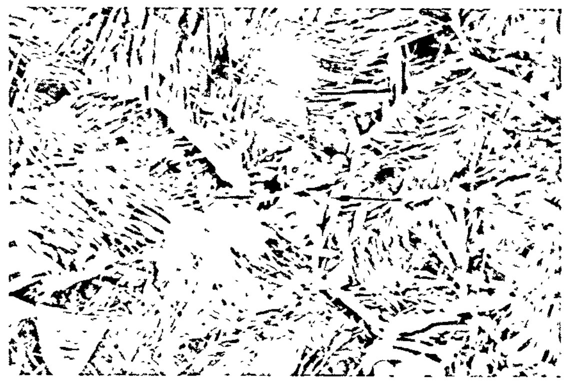
WELD METAL FUSION LINE



HAZ-1 MM

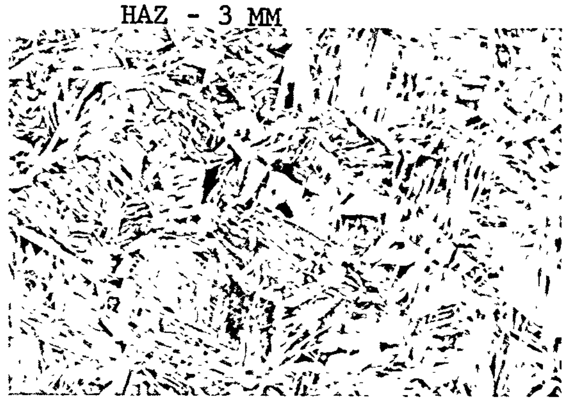


HAZ -2MM



HAZ - 3 MM

HAZ-4MM



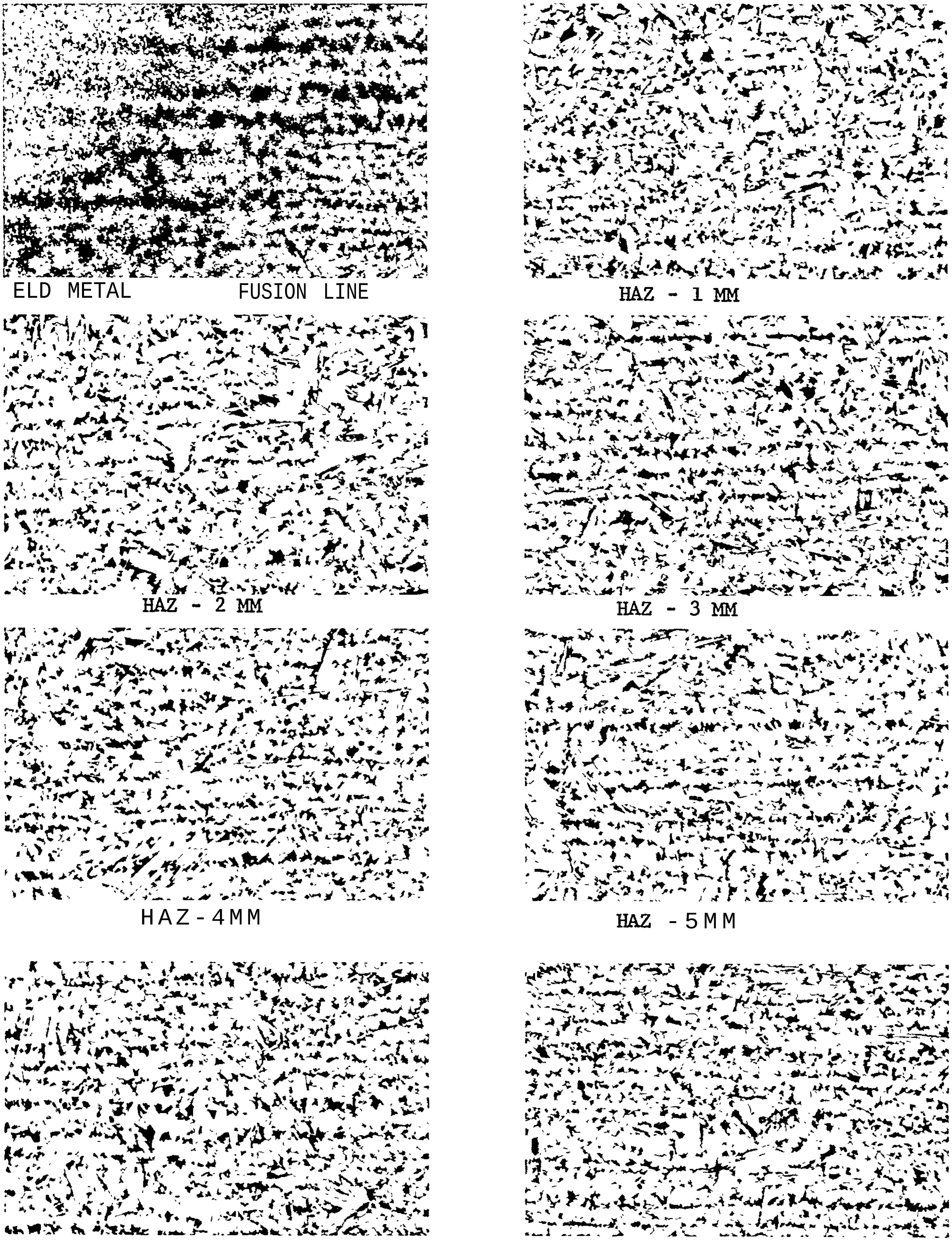
HAZ-5 MM

HAZ-7MM

HAZ-9MM

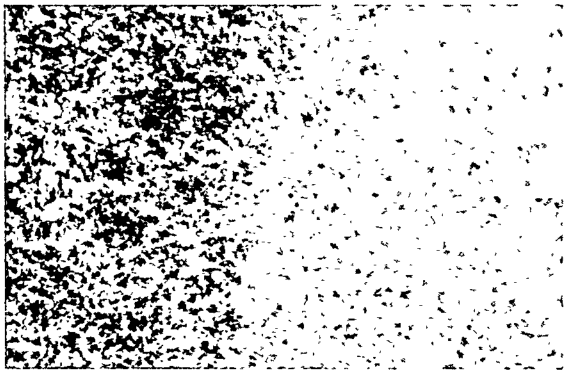
(2% NITAL ETCH - 100 X)

FIGURE 38 - PHOTOMICROGRAPHS OF ES WELDEMENT IN GRADE B MATERIAL

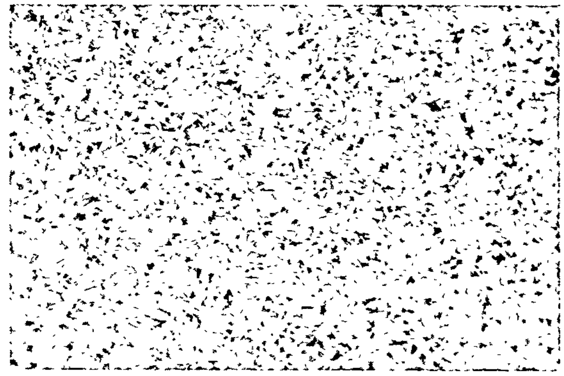


(2% NITAL ETCH - 100 X)

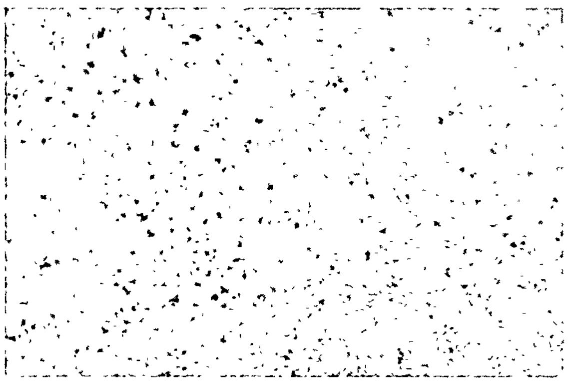
FIGURE 39 - PHOTOMICROGRAPHS OF MMA WELDEMENT GRADE CS MATERIAL



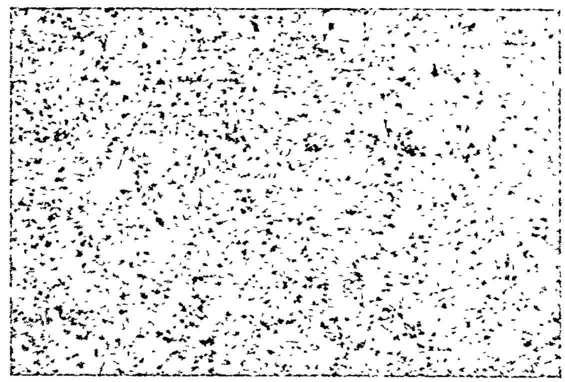
WELD METAL FUSION LINE



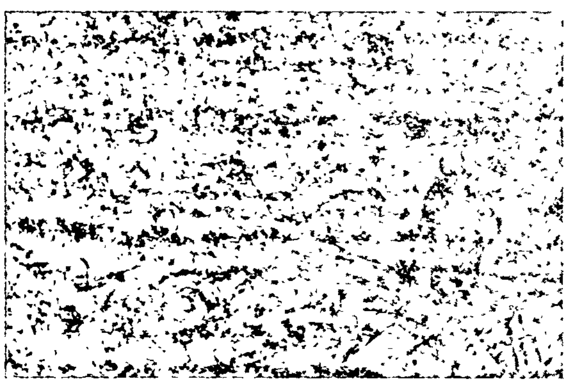
HAZ - 1 MM



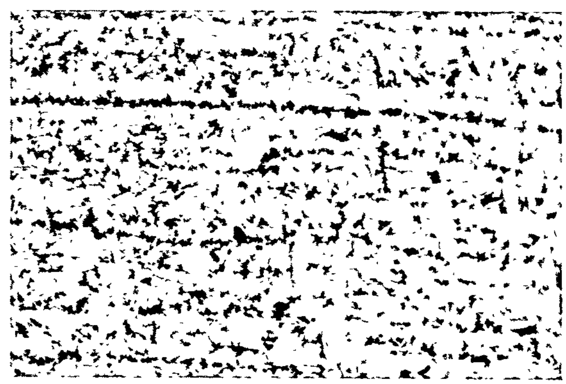
HAZ - 2 MM



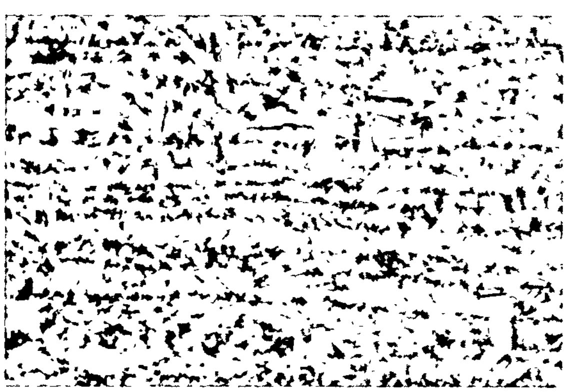
HAZ - 3 MM



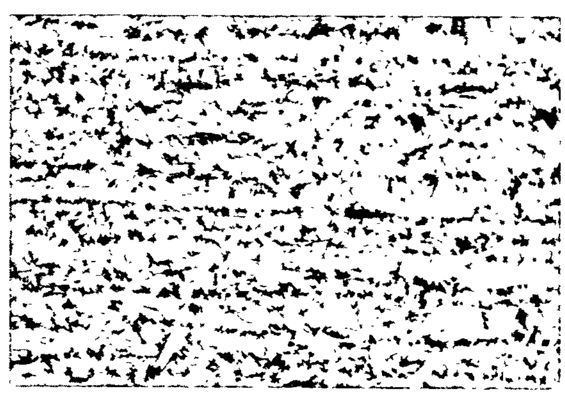
HAZ - 4 MM



HAZ - 5 MM



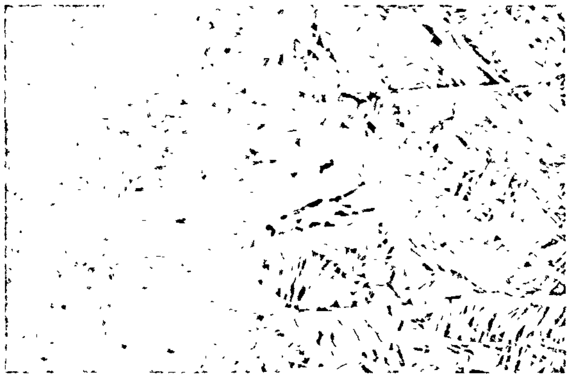
HAZ - 7 MM



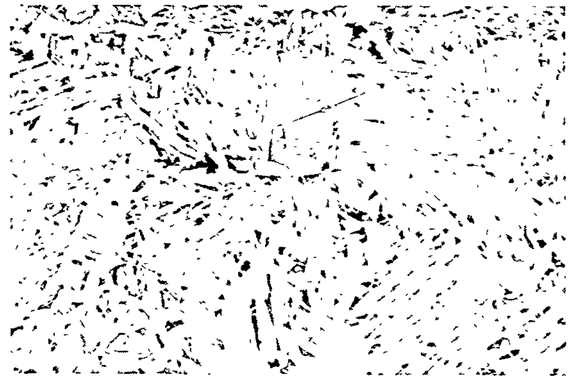
HAZ - 9 MM

(2% NITAL ETCH - 100 X)

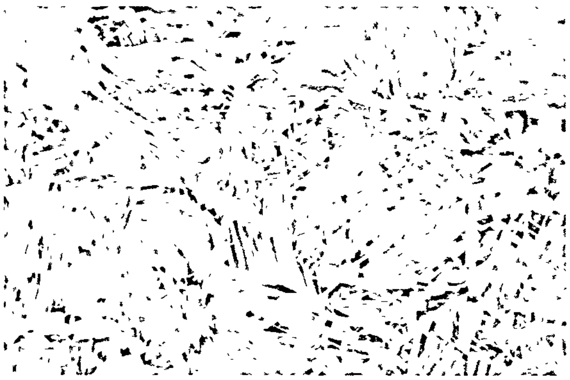
FIGURE 40 - PHOTOMICROGRAPHS OF SAW WELDMENT IN GRADE CS MATERIAL



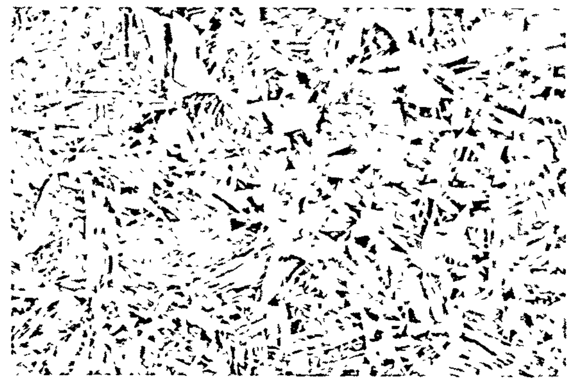
WELD METAL FUSION LINE



HAZ-l MM

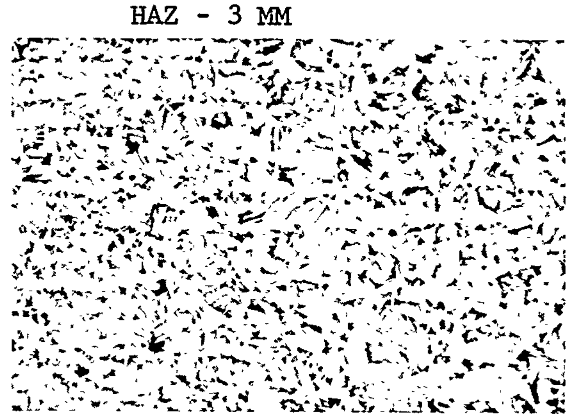


HAZ-2MM



HAZ - 3 MM

HAZ-4MM



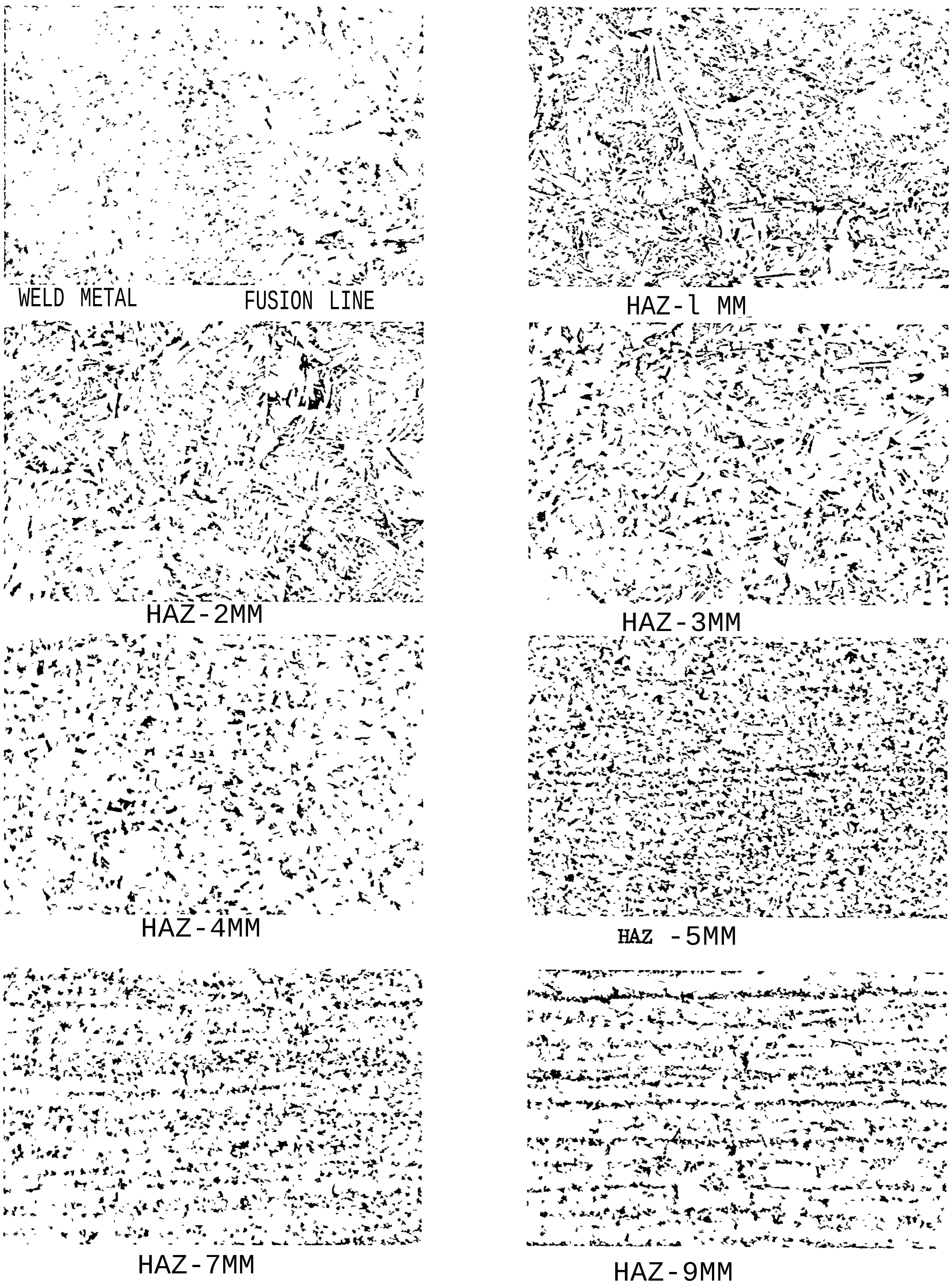
HAZ - 5 m

HAZ-7MM

HAZ - 9 MM

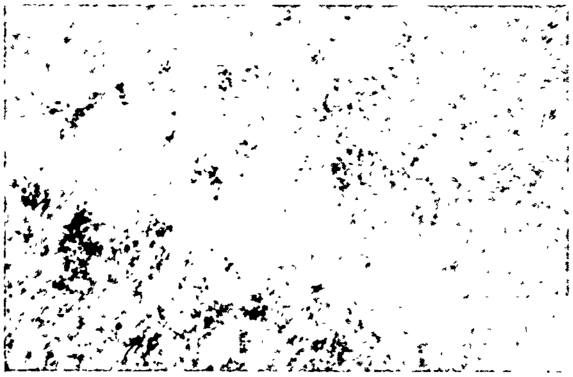
(2% NITAL ETCH - 100 X)

FIGURE 41 - PHOTOMICROGRAPHS OF EG WELDMENT IN GRADE CS MATERIAL

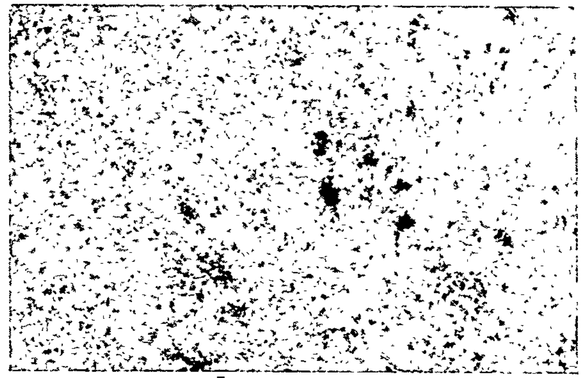


(2% NITAL ETCH - 100 X)

FIGURE 42 - PHOTOMICROGRAPHS OF ES WELDMENT IN GRADE CS MATERIAL



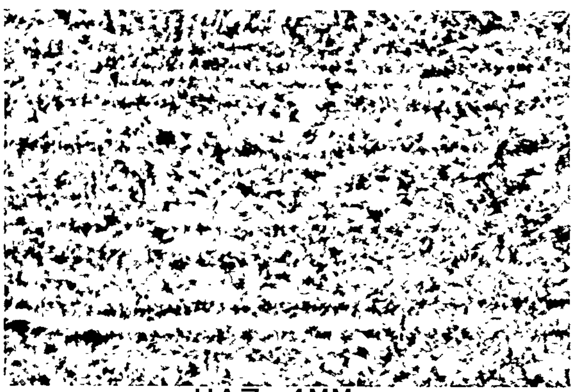
WELD METAL FUSION LINE



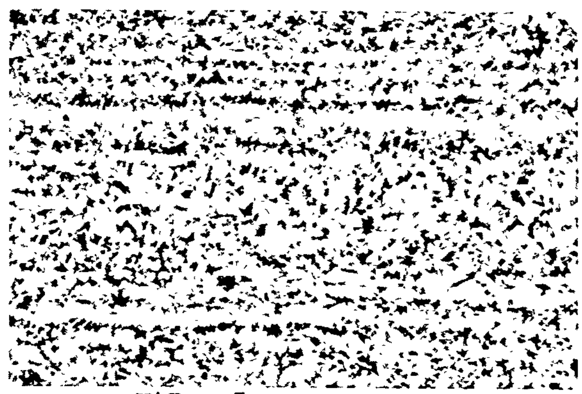
HAZ-1 MM

HAZ-2MM

HAZ - 3 MM

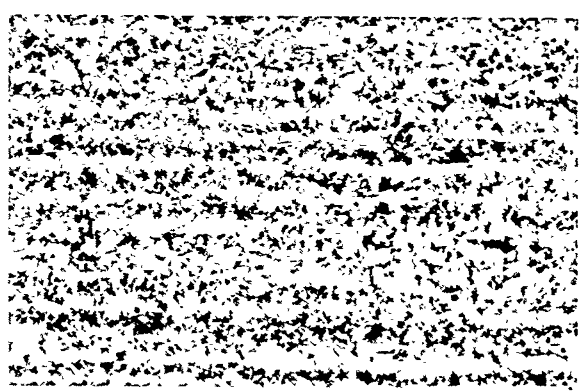


HAZ-4MM



HAZ - 5 MM

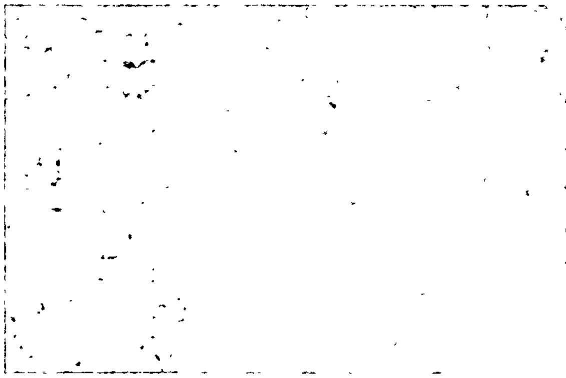
HAZ-7MM



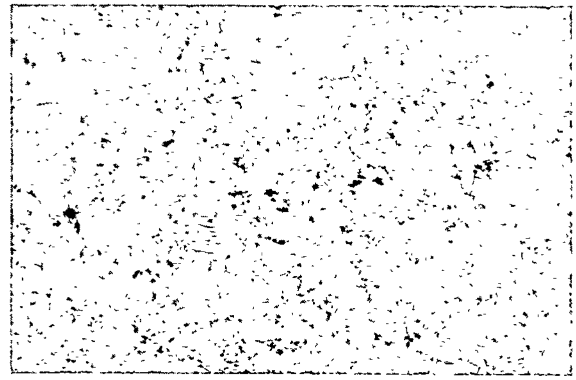
HAZ-9MM

(2% NITAL ETCH - 100 X)

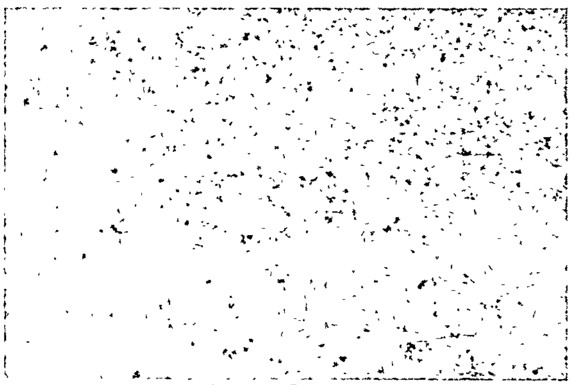
FIGURE 43 - PHOTOMICROGRAPHS OF MMA WELDMENT IN GRADE EH36 MATERIAL



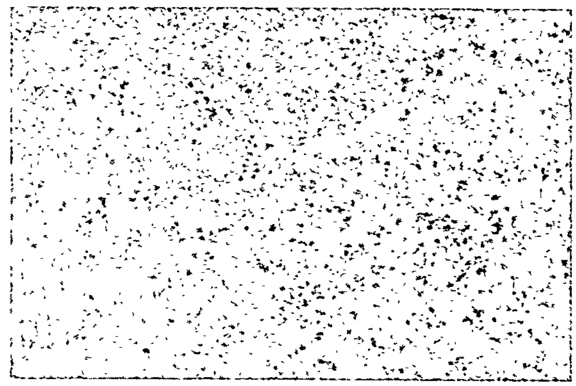
WELD METAL FUSION LINE



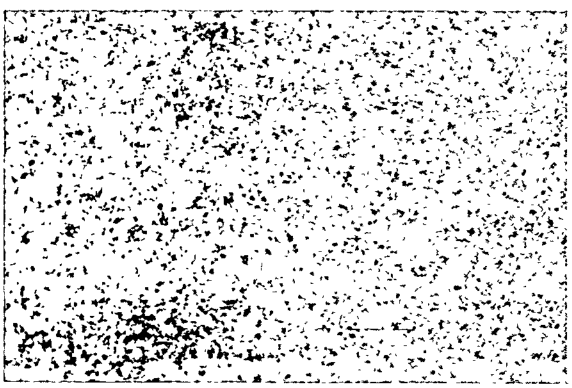
HAZ - 1 MM



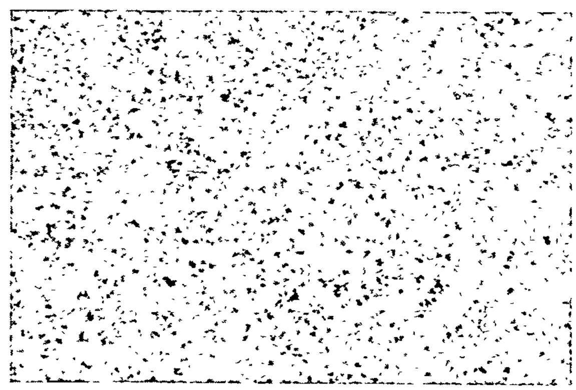
HAZ - 2 MM



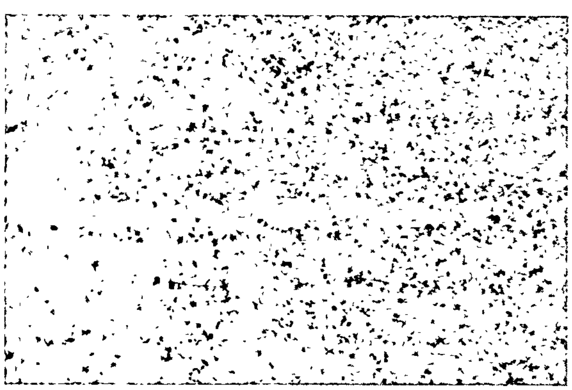
HAZ - 3 MM



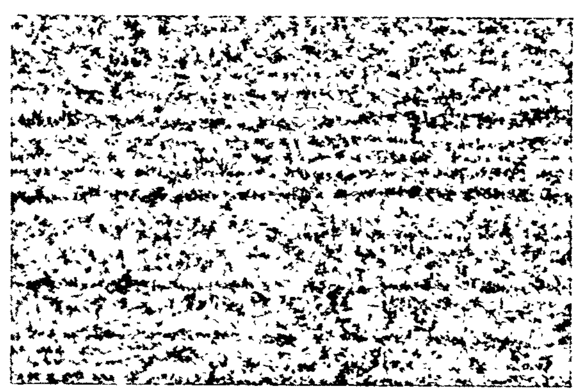
HAZ - 4 MM



HAZ - 5 MM



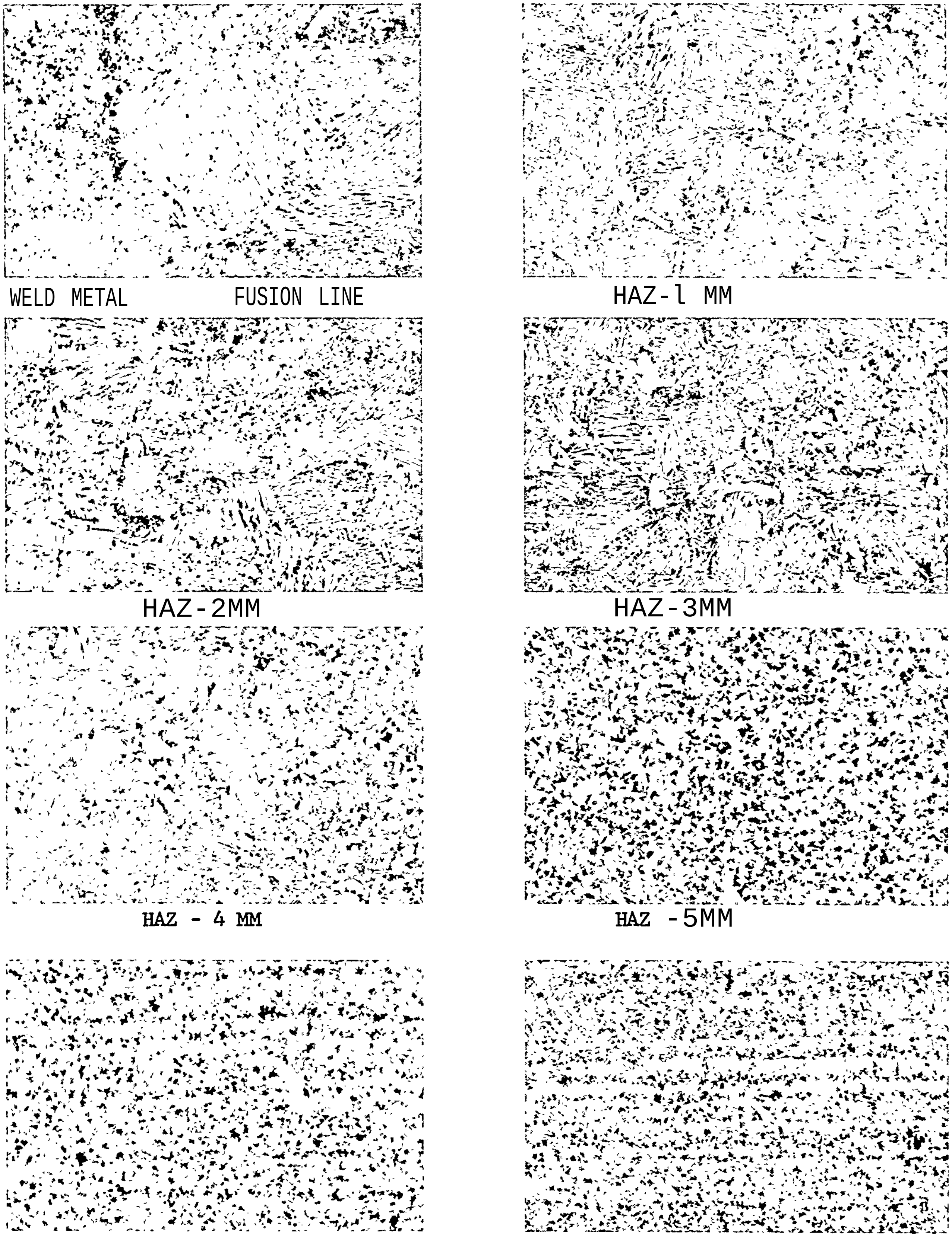
HAZ - 7 MM



HAZ - 9 MM

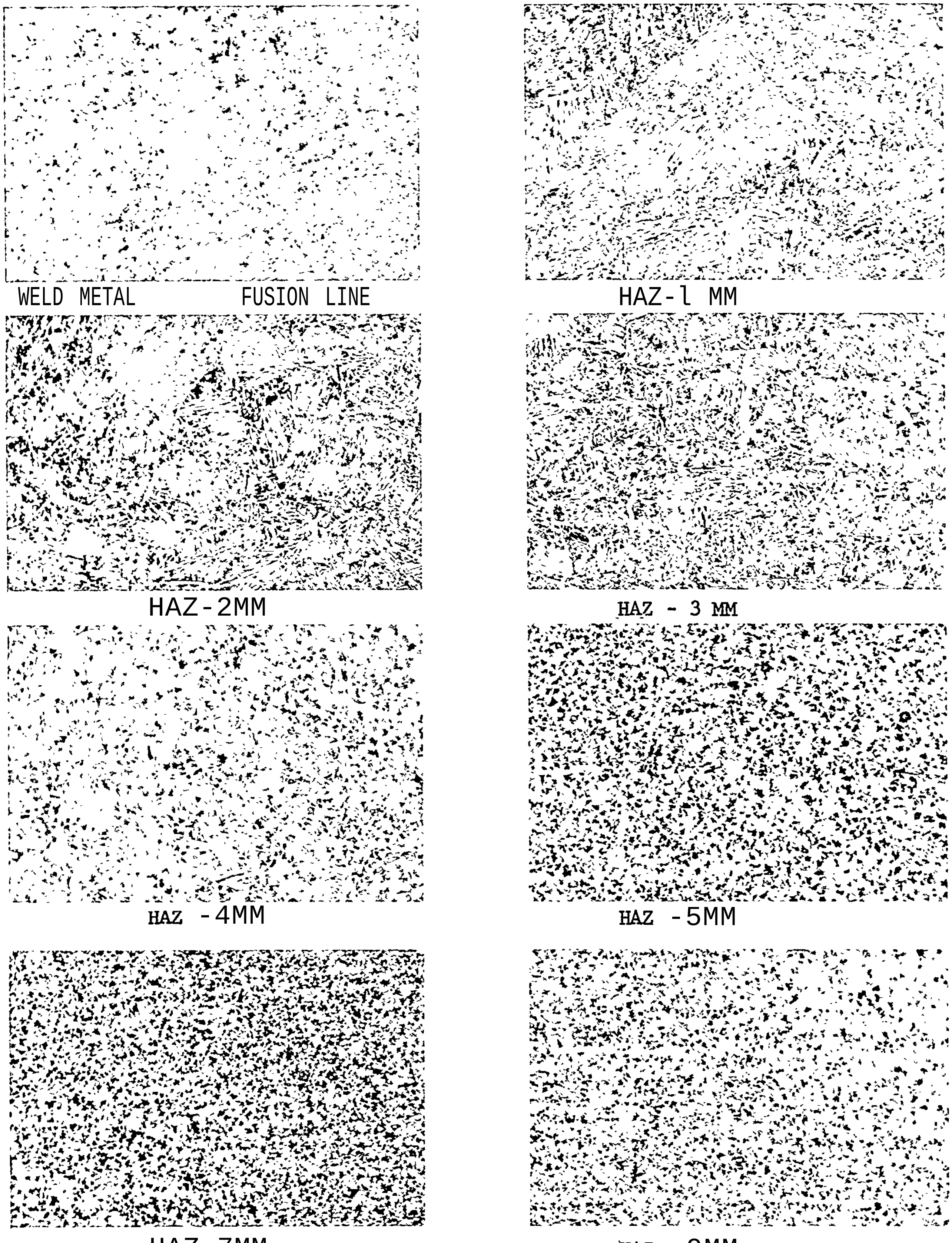
(2% NITAL ETCH - 100 X)

FIGURE 44 - PHOTOMICROGRAPHS OF SAW WELDMENT IN GRADE EH36 MATERIAL



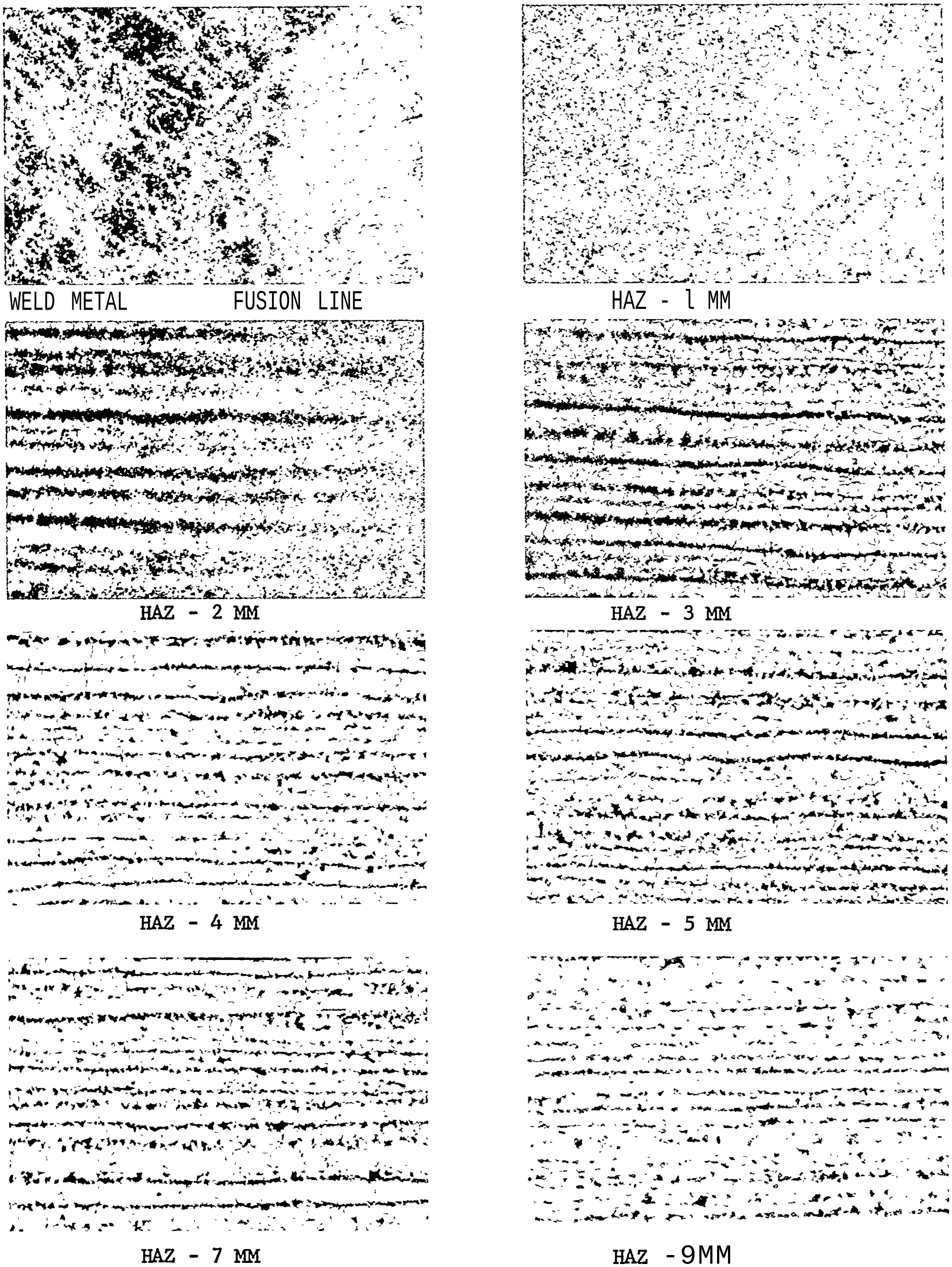
(2% NITAL ETCH - 100 X)

FIGURE 45 - PHOTOMICROGRAPHS OF EG WELDMENT IN GRAOE EH36 MERIAL



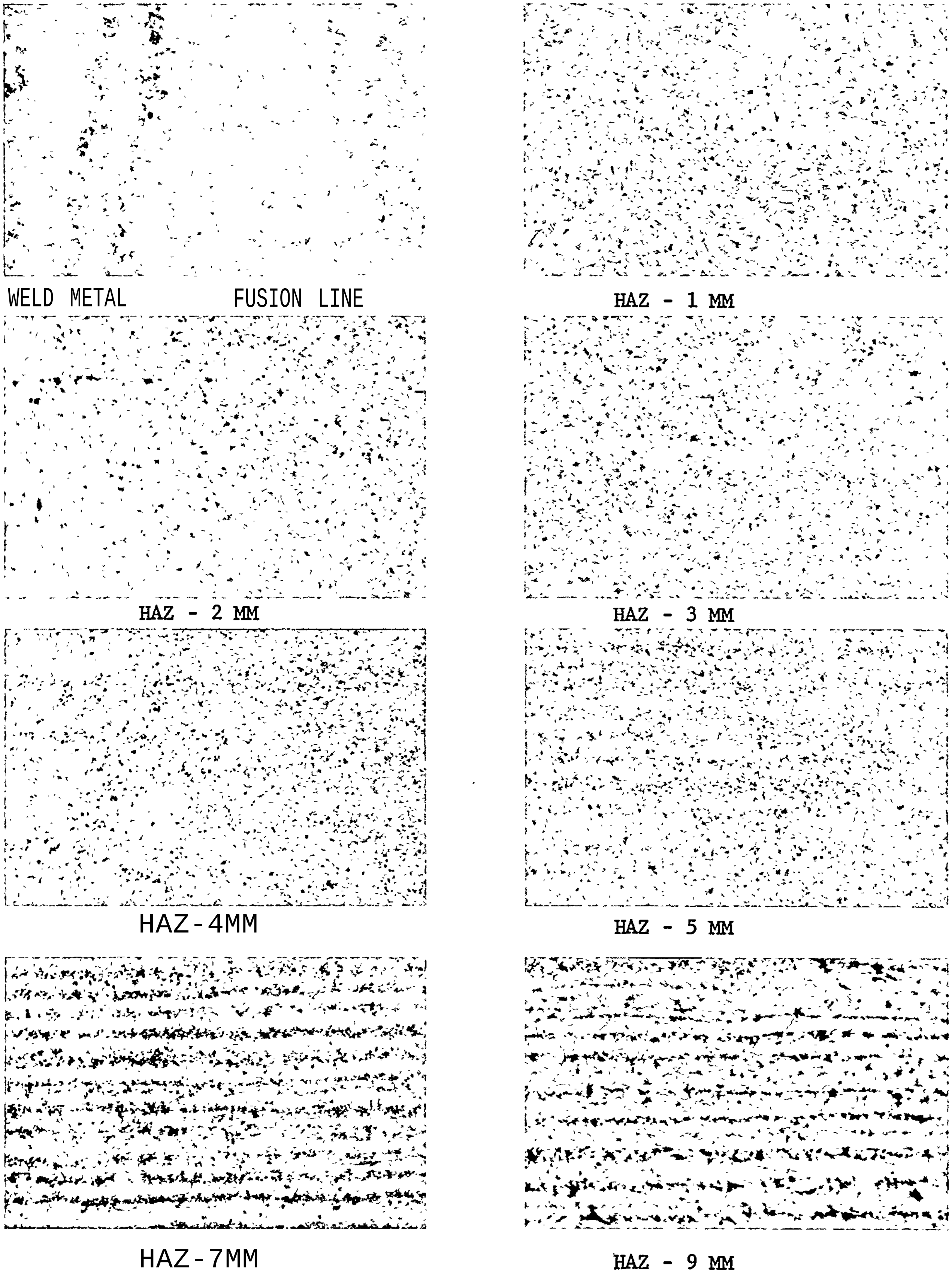
(2% NITAL ETCH - 100 X)

FIGURE 46 - PHOTOMICROGRAPHS-OF ES WELDMENT IN GRADE EH36 MATERIAL



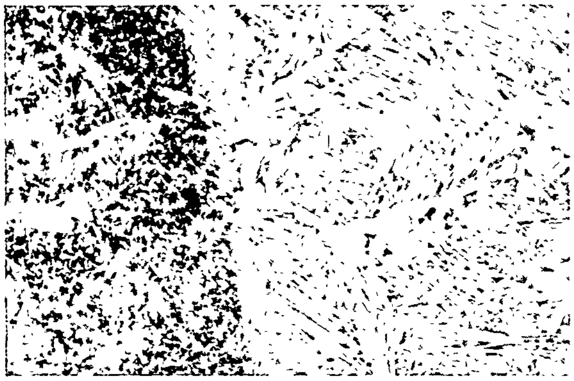
(2% NITAL ETCH - 100 X)

FIGURE 47 - PHOTOMICROGRAPHS OF MMA WELDMENT IN ASTM A203 GRADE A MATERIAL

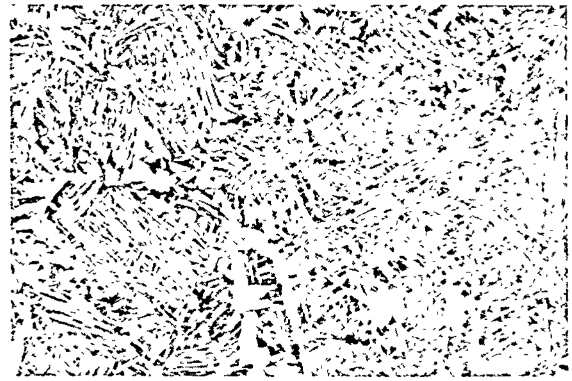


(2% NITAL ETCH - 100 X)

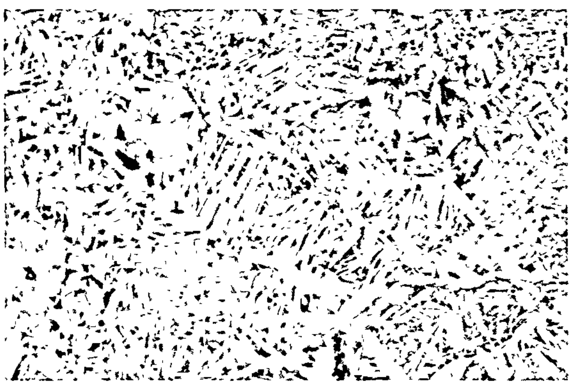
FIGURE 48 - PHOTOMICROGRAPHS OF SAW WELDMENT IN ASTM A203 GRADE A MATERIAL



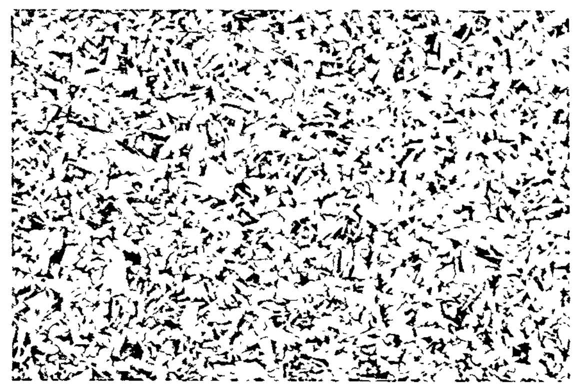
WELD METAL FUSION LINE



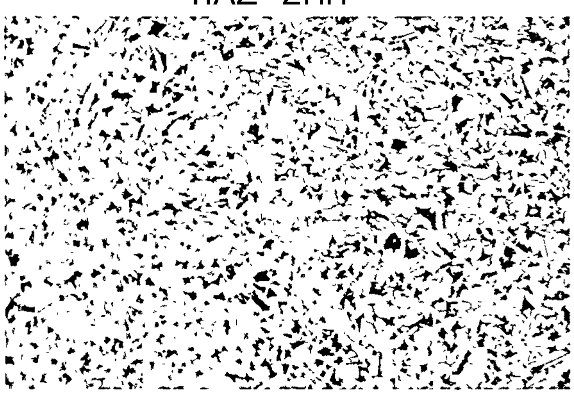
HAZ-l MM



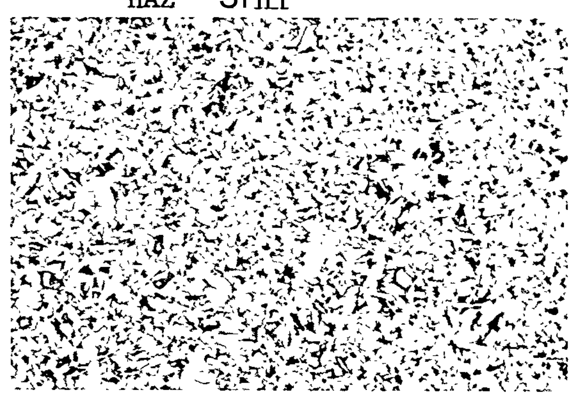
HAZ-2MM



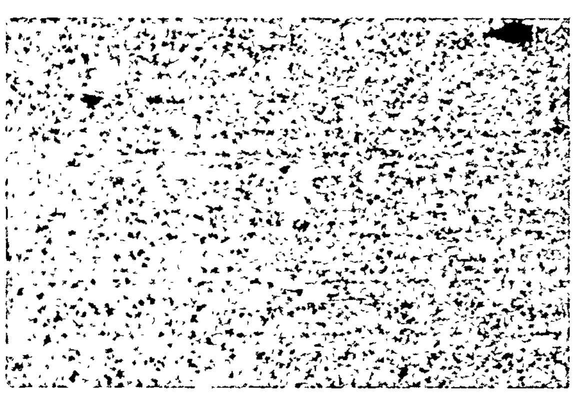
HAZ -3MM



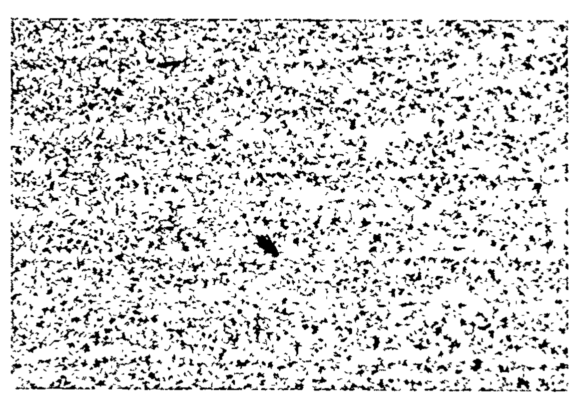
HAZ -4MM



HAZ -5MM



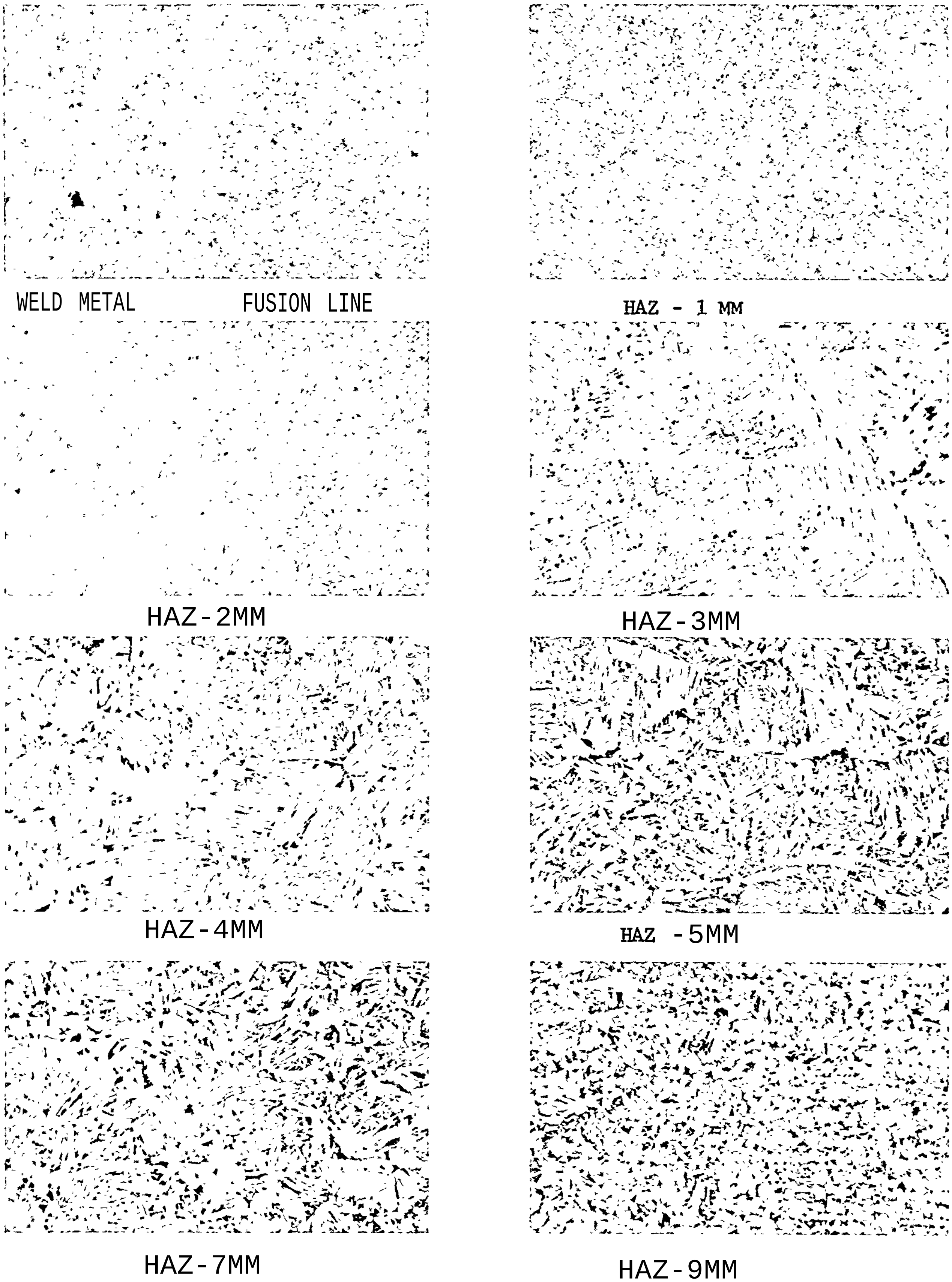
HAZ-7MM



HAZ-9MM

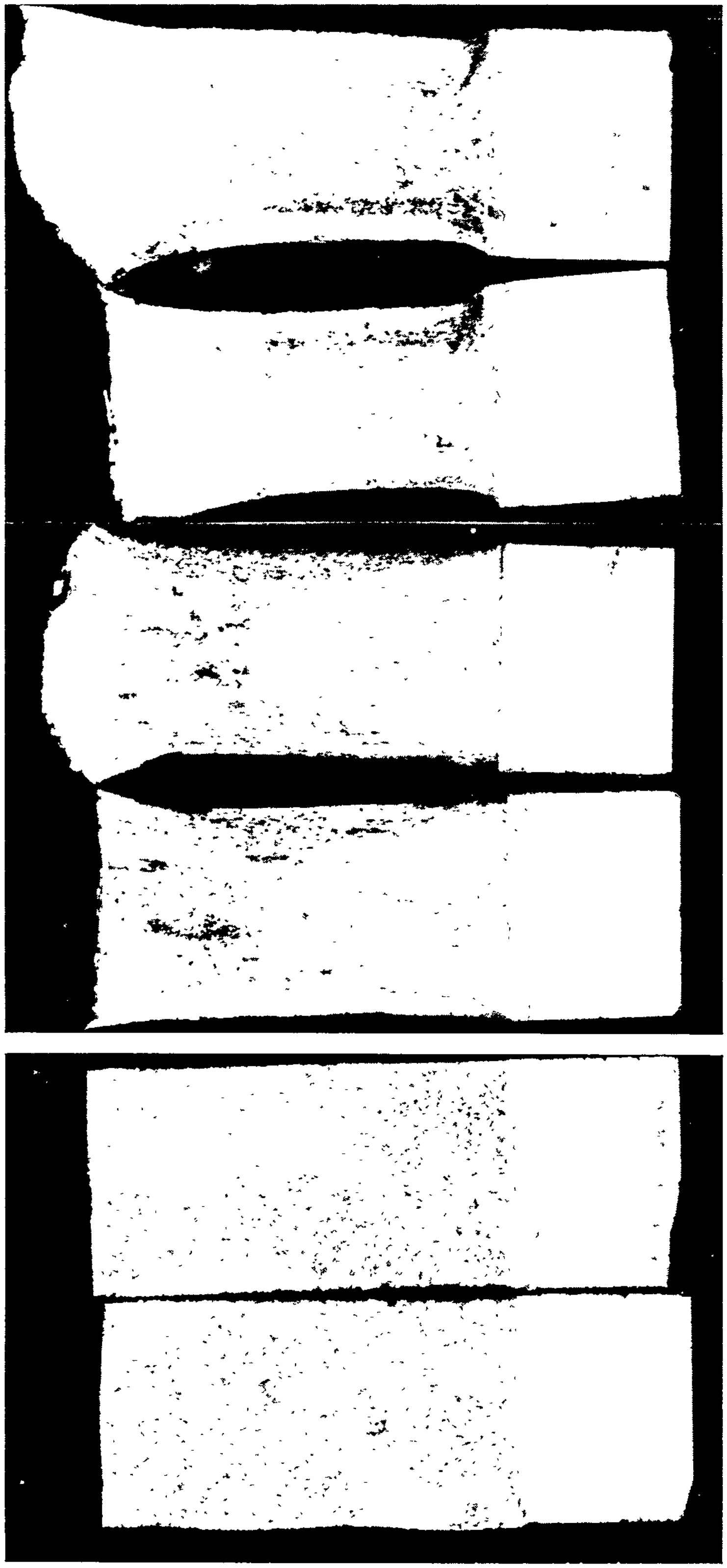
(2% NITAL ETCH - 100 X)

FIGURE 49 - PHOTOMICROGRAPHS OF EG WEIDMENT IN ASTM A203 GRADE A MATERIAL



(2% NITAL ETCH - 100 X)

FIGURE 50 - PHOTOMICROGRAPHS OF ES WELDMENT OF ASTM A203 GRADE A MATERIAL



DUCTILE FRACTURE
1045 FT-LJ3S
100% SHEAR
MM HAZ GRADE (CS
TESTED AT 70F

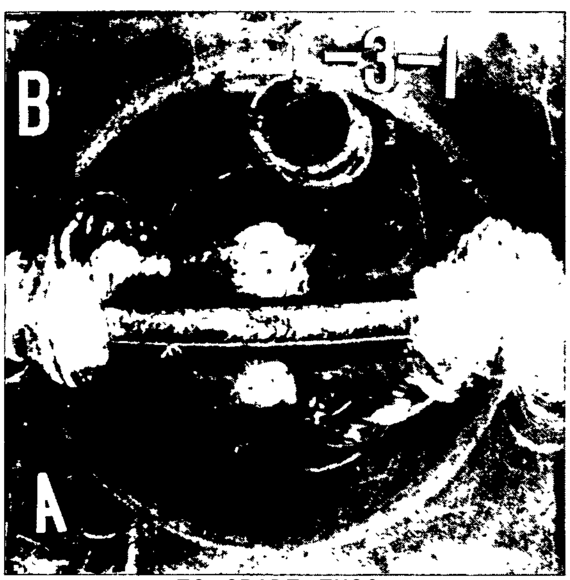
MIXED FRACTURE
300 FT-LBS
55% SHEAR
ES HAZ GRADE CS
TESTED AT 70F

BRITTLE FRACTURE
45 FT-LBS
0% SHEAR
ES HAZ GRADE CS
TESTED AT -4F

FIGURE 51 - RELATIONSHIP BETWEEN DYNAMIC TEAR ENERGY AND FRACTURE APPEARANCE

MMA - GRADE CS
(TEST TEMPERATURE 20 F)

SAW ASTM A203 GRADE A
(TEST TEMPERATURE OF)



EG GRADE EH36
(TEST TEMPERATURE OF)

ES GRADE B
TEST TEMPERATURE 120F)

FIGURE 52 - REPRESENTATIVE EXPLOSION BULGE SPECIMENS SHOWING NO CRACK AFTER 3 SHOTS

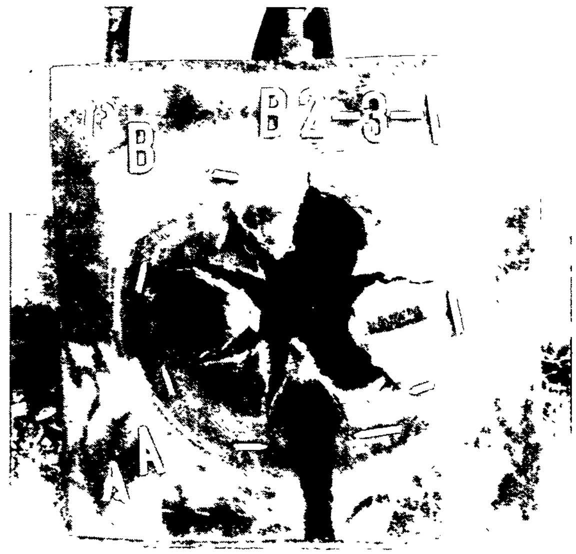
NO. B1 AFTER 1 SHOT (TENSION SIDE)

NO. B1 AFTER 1 SHOT (COMPRESSION SIDE)

(TEST TEMPERATURE 30F)

FIGURE 53 - MMA GRADE B EXPLOSION BULGE SPECIMEN

NO. BIA AFTER 3 SHOTS

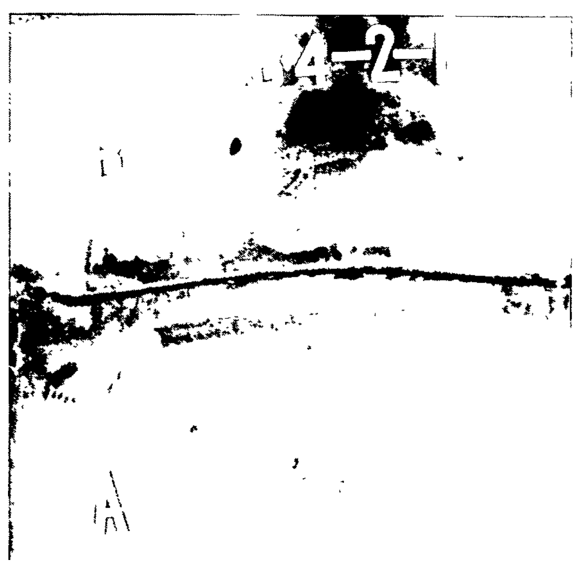


NO. B2 AFTER 3 SHOTS

(TEST TEMPERATURE 120F)

FIGURE 54 - MM GRADE B EXPLOSION BULGE SPECIMENS

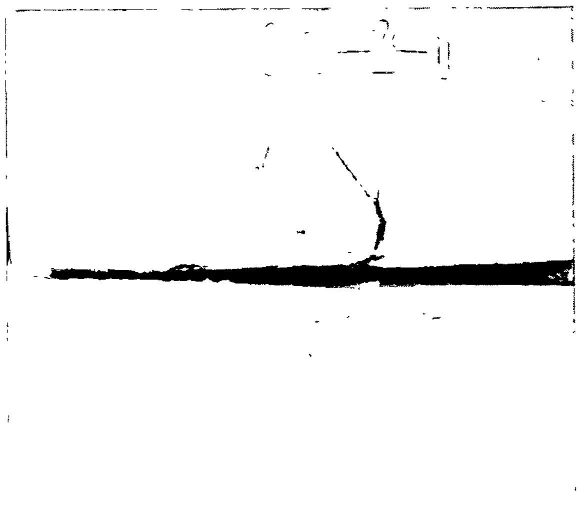
NO. B3 AFTER 3 SHOTS



NO. B4 AFTER 2 SHOTS

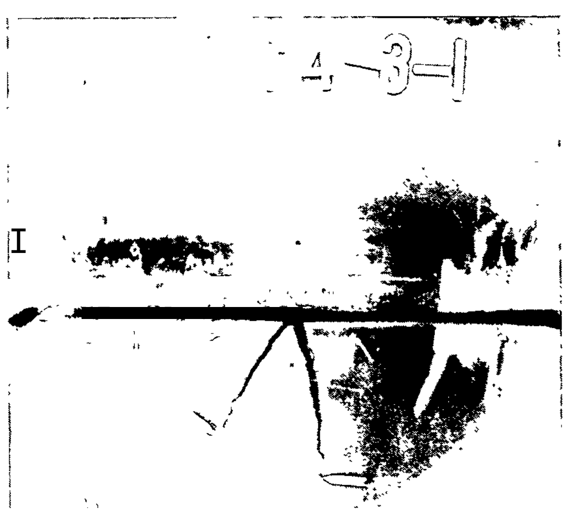
(TEST TEMPERATURE 120F)

FIGURE 55 - EG GRADE B EXPLOSION BULGE SPECIMENS



NO. C3 AFTER 2 SHOTS

NO. C3A AFTER 3 SHOTS



NO. C4 AFTER 3 SHOTS
(TEST TEMPERATURE 20F)

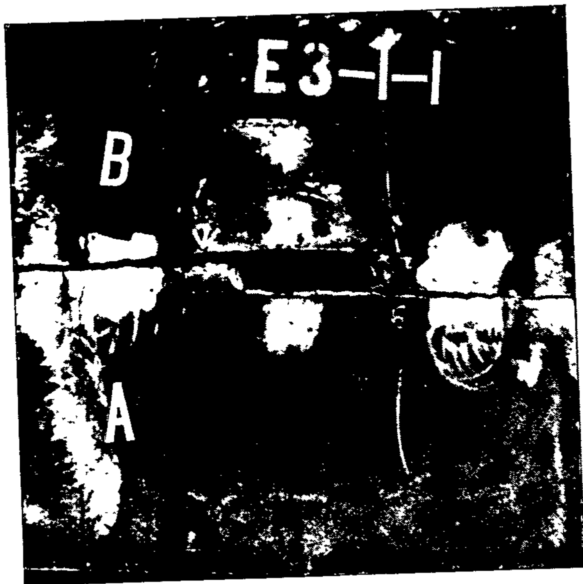
FIGURE 56 - EG GRADE CS EXPLOSION BULGE SPECIMENS

NO; C6 AFTER 3 SHOTS
(TEST TEMPERATURE 20F)

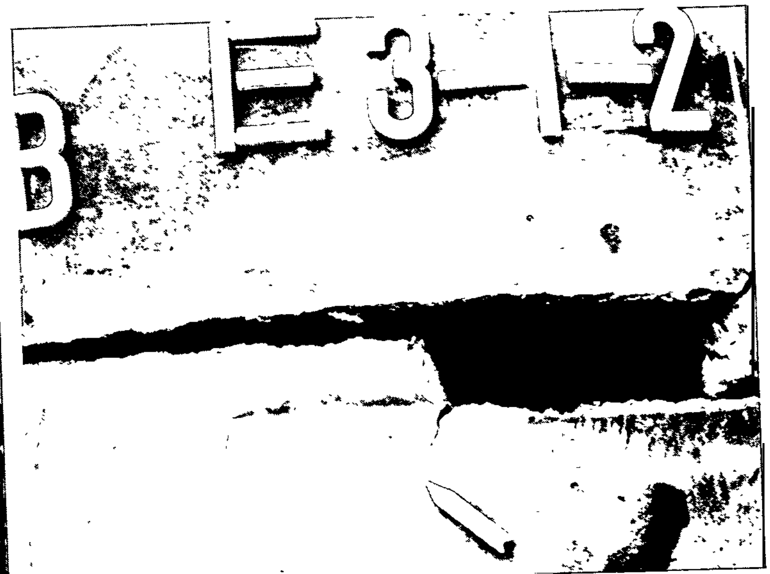
FIGURE 57 - SAW GRADE CS EXPLOSION BULGE SPECIMEN

NO. El AFTER 3 SHOTS
(TEST TEMPERATURE OF)

FIGURE 58 - MMA GRADE EH36 EXPLOSION BULGE SPECIMEN

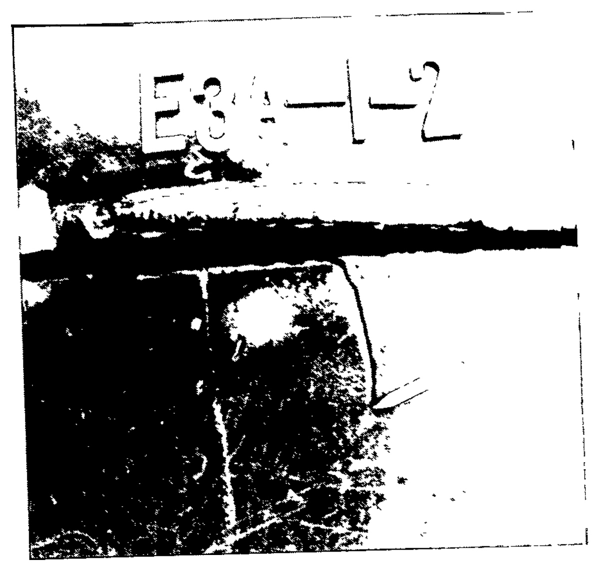


NO. E3 AFTER 1 SHOT



NO. E3 AFTER 1 SHOT

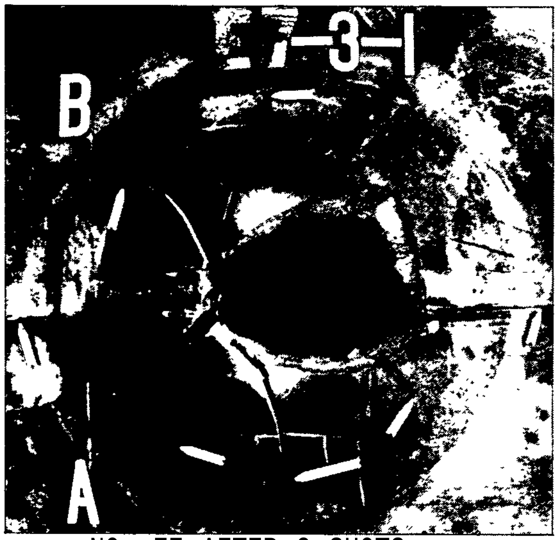
NO. E3A AFTER 1 SHOT



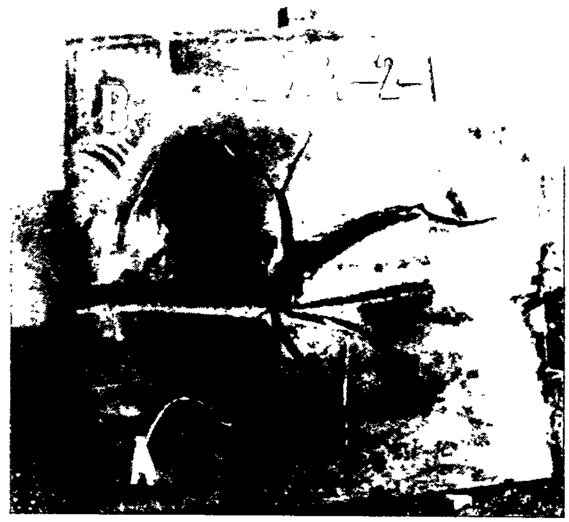
NO. E3A AFTER 1 SHOT

(TEST TEMPERATURE OF)

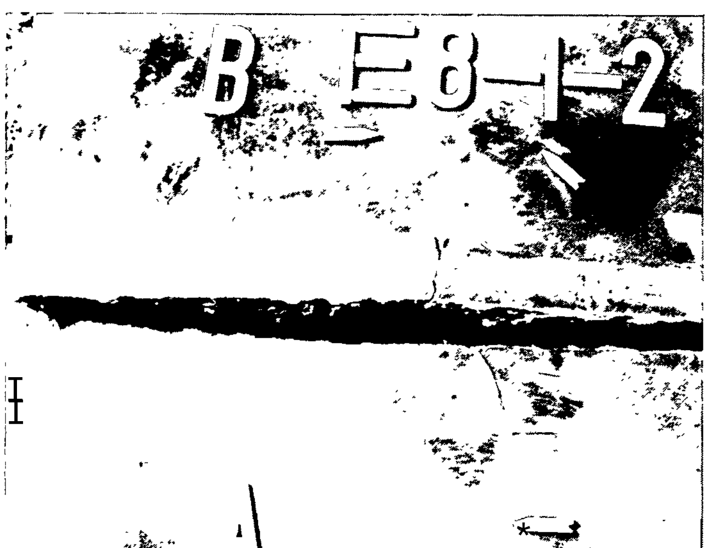
FIGURE 59 - EG GRADE EH36 EXPLOSION BULGE SPECIMENS



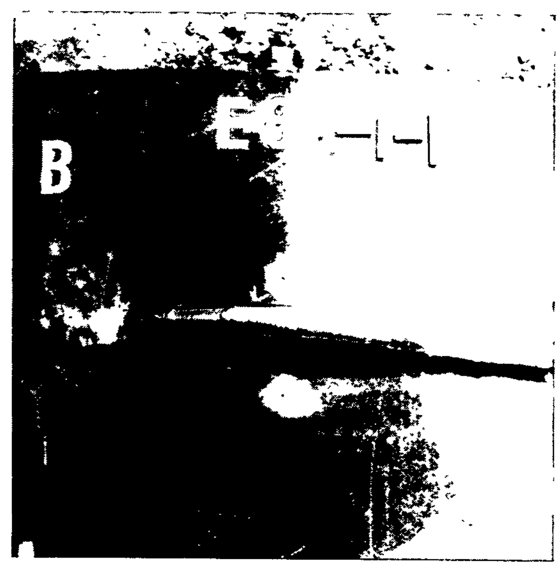
NO. E7 AFTER 3 SHOTS



NO. E7A AFTER 2 SHOTS



NO E8 AFTER 1 SHOT



NO. E8A AFTER 1 SHOT

(TEST TEMPERATURE 0F)

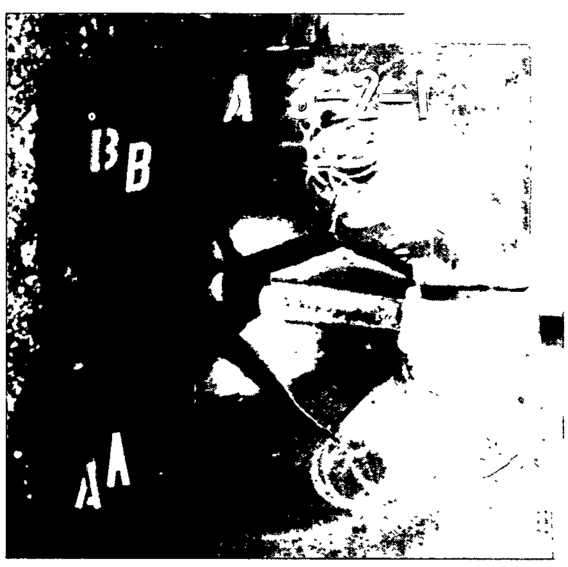
FIGURE 60 - ES GRADE EH36 EXPLOSION BULGE SPECIMENS

NO. Al AFTER 3 SHOTS

NO. A2 AFTER 3 SHOTS

(TEST TEMPERATURE OF)

FIGURE 61 - MMA ASTM A203 GRADE A EXPLOSION BULGE SPECIMENS



NO. A3 AFTER 2 SHOTS

NO. A4 AFTER 2 SHOTS

(TEST TEMPERATURE OF)

FIGURE 62 - EG ASTM A203 GRADE A EXPLOSION BULGE SPECIMENS

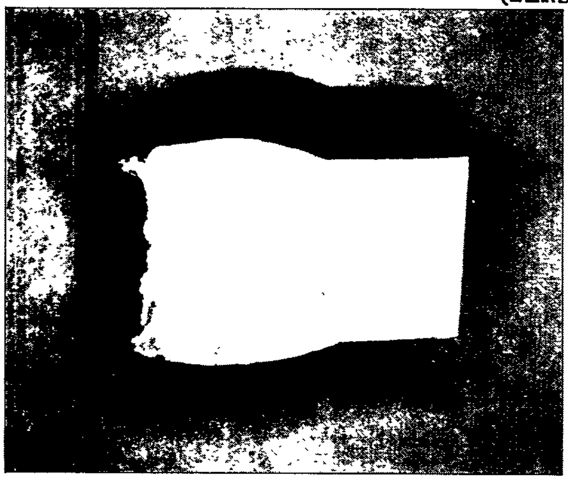
NO. A7 AFTER 2 SHOTS

NO. A8 AFTER 2 SHOTS

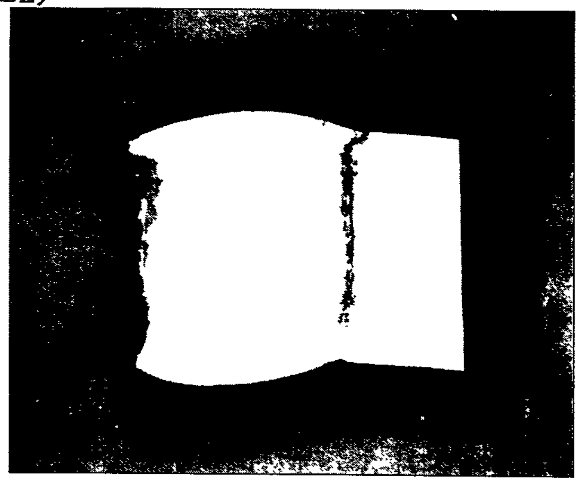
(TEST TEMPERATURE OF)

FIGURE 63 - ES ASTM A203 GRADE A EXPLOSION BULGE SPECIMENS

(TENSION SIDE)

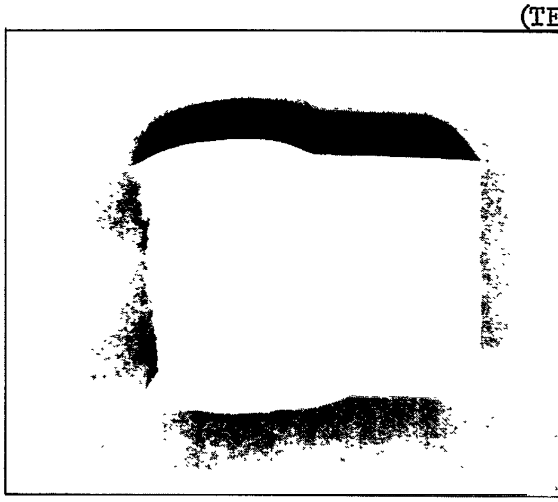


EG GRADE B NO. B4

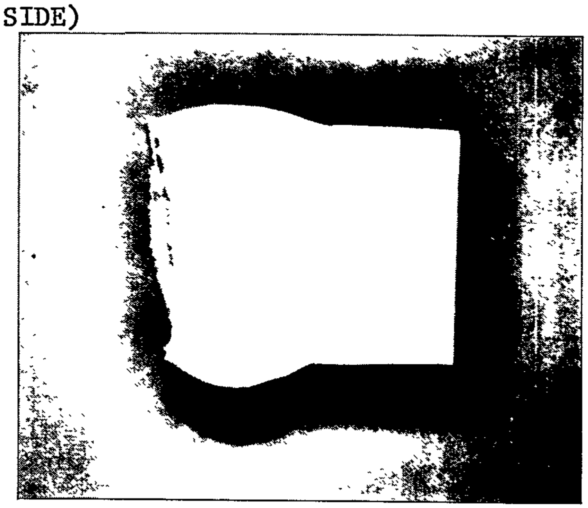


EG GRADE CS NO. C4

(TENSION SIDE)



EG GRADE CS NO. C4

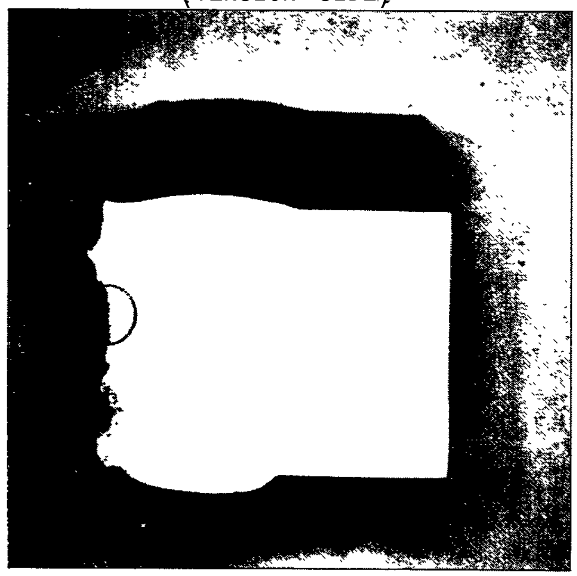


ES ASTM A203 GRADE A NO. A7

(10% NITAL ETCH - ACTUAL SIZE)

FIGURE 64 - MACROSECTIONS SHOWING AREAS OF SEPARATION IN EG AND ES WELDS

(TENSION SIDE)

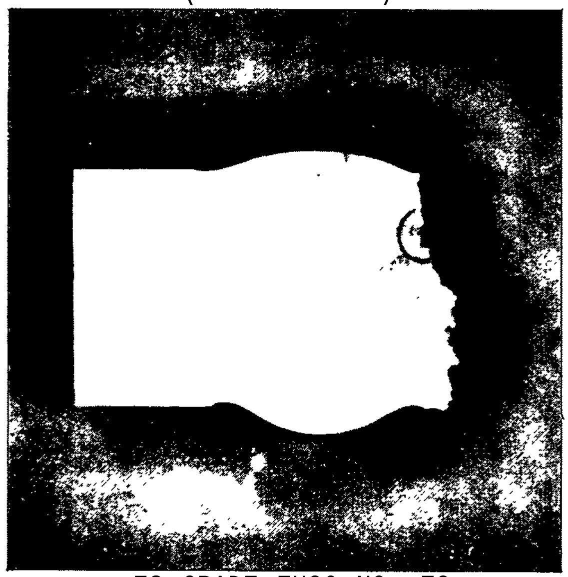


EG GRADE EH36 NO. E3
(10% NITAL ETCH - ACTUAL SIZE)

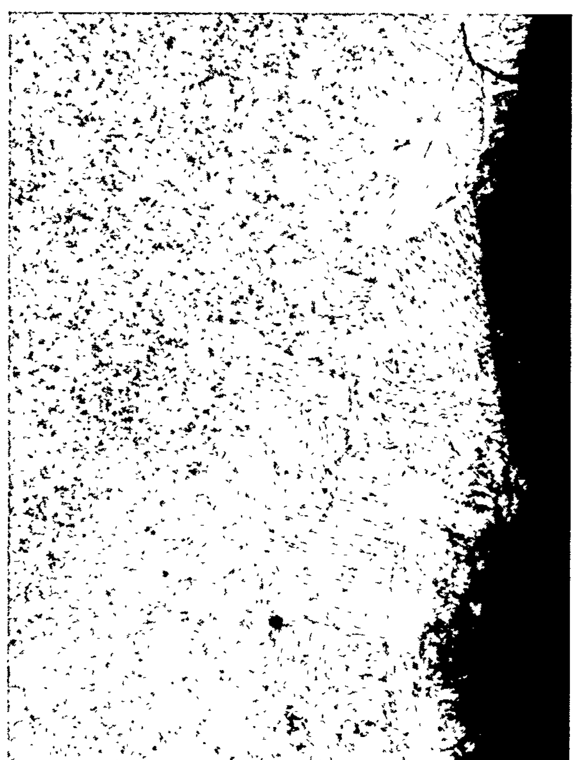
MICROGRAPH OF ENCIRCLED AREA ABOVE
(2% NITAL ETCH - 100X)

FIGURE 65 - MACROSECTION AND MICROGRAPH SHOWING AREA OF SEPARATION IN EG WELD

(TENSION SIDE)



ES GRADE EH36 NO. E8
(10% NITAL ETCH - ACTUAL SIZE)



MICROGRAPH OF ENCIRCLED AREA ABOVE
(2% NITAL ETCH - 100X)

FIGURE 66 - MACROSECTION AND MICROGRAPH SHOWING AREA OF SEPARATION IN ES WELD